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A re-examination of churchite.

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In the course of a study of certain cerium minerals, a spectrogram of churchite was taken and it was noticed that the cerium lines were barely visible, whereas the yttrium lines were very strong. We therefore decided to re-investigate this species.

Churchite was originally described by A. H. Church in 1865, and named by C. G. Williams in the same year.[1] The specimens were collected by R. Talling from an unnamed locality in Cornwall. It has only been analysed once, by Church, who showed it to be a hydrated phosphate of rare-earths and lime; his quantitative data have been recalculated and included in table I. Church obtained qualitative reactions for the cerium group of rare-earths, and for cerium itself,[2] but made no attempt to determine the ratio of cerium to yttrium earths; he assumed a mean molecular weight for the rare-earths which would correspond to R_2O_3 324, essentially a mixture of cerium earths with but little yttria, but did not adduce any evidence for this assumption. As will be shown below, churchite actually contains very little cerium, and is essentially a phosphate of yttrium with minor amounts of other rare-earths, principally neodymium, erbium, and cerium; but the standard text-books[3] have listed churchite as 'a phosphate of cerium (didymium)

[1] A. H. Church, Chem. News, 1865, vol. 12, no. 302 (September 15), p. 121. C. G. Williams, ibid., no. 307 (October 20), p. 183. A. H. Church, Journ. Chem. Soc. London, 1865, ser. 2, vol. 3, p. 259.

[2] A solution of the sulphates of the rare-earths gave a precipitate with potassium sulphate; the oxalate, on ignition, left an orange-brown oxide which dissolved in hydrochloric acid with evolution of chlorine.

[3] For example, Dana, System of mineralogy 6th edit., 1892, p. 820; 7th edit., 1951, p. 773.

and calcium', overlooking the fact that Church only claimed it as a phosphate of the cerium earths and only gave qualitative evidence of the presence of cerium, to which C. G. Williams added qualitative evidence of the presence of neodymium or praseodymium or both.

In 1922, H. Laubmann[1] described a phosphate of yttrium from the Nitzelbuch mine, Auerbach, Bavaria, under the name weinschenkite, a name which unfortunately was used almost simultaneously by G. Murgoci[2] for a variety of hornblende; an analysis by F. Henrich showed that the mean molecular weight of the rare-earths was R_2O_3 251·8, and the formula for the mineral $YtPO_4.2H_2O$, with some Er and probably Tb replacing Yt. In 1935 a new analysis (table I) and re-determination of the mean molecular weight of the rare-earths by F. Henrich[3] gave R_2O_3 248·1; the relative abundances of the rare-earths were determined by optical and X-ray spectrography. In 1942 H. Strunz[4] gave unit-cell dimensions for weinschenkite (from Auerbach) and noted its structural similarity to gypsum.

The only other known occurrence of a rare-earth phosphate of this type is at Kelly Bank mine, Vesuvius, Rockbridge County, Virginia. From here C. Milton, K. J. Murata, and M. M. Knechtel[5] describe material agreeing in optical data and X-ray powder photograph with Bavarian weinschenkite; it was not analysed, but a spectrographic study showed it to be an yttrium phosphate essentially similar to the Bavarian except for a rather higher proportion of Yb; its specific gravity is 3·263 and the mean molecular weight of the rare-earths, 257·0, is practically the same as that for the Bavarian and, as will be seen below, the Cornish material. From a study of the paragenesis,

[1] F. Henrich, Ber. Deutsch. Chem. Gesell., 1922, vol. 55, Abt. B, p. 3013 (October 14). [M.A. 2–12.] H. Laubmann, Geognost. Jahreshefte, Geol. Landesunters. München, 1923, vol. 35 (for 1922), p. 193. [M.A. 2–522.] A preliminary note by F. Henrich appeared in Edel-Erden und -Erze, 1921, vol. 2, p. 181, but the present authors have not been able to see this paper, and it is not clear whether the name weinschenkite appears in it or not.

[2] G. Murgoci, Compt. Rend. Acad. Sci. Paris, 1922, vol. 175, p. 372 (August 21) and p. 426 (September 4). [M.A. 2–221.]

[3] F. Henrich, Journ. Prakt. Chem., 1935, vol. 142, p. 1.

[4] H. Strunz, Naturwiss., 1942, vol. 30, p. 64. [M.A. 8–368.] We adopt the setting with β 113° 24′, given in Dana (7th edit., vol. 2, p. 772) for the structure cell, and not the setting with β 129° 24′ adopted by Strunz. The transformation matrix from Strunz's to our setting is $\|\bar{1}0\bar{1}/0\bar{1}0/001\|$. This setting corresponds to that adopted by Dana (loc. cit.) for gypsum, brushite, and pharmacolite.

[5] C. Milton, K. J. Murata, and M. M. Knechtel, Amer. Min., 1944, vol. 29, p. 92. [M.A. 9–54.]

Milton, Murata, and Knechtel conclude that the Virginian mineral probably owes its origin to a biochemical concentration of yttrium in chestnut and hickory leaves.

A new analysis (table I) made on 105 mg. of Cornish churchite from the British Museum specimen (B.M. 40636), purchased from R. Talling

TABLE I. Chemical analyses and unit-cell contents of churchite.

	1.	2.	3.	4.		1a.	3a.	4a.
$(Yt,Er)_2O_3$ ...	41·37				Yt ...	2·95		
$(La,Nd)_2O_3$ ...	7·99	54·6	52·47	52·90	Er ...	0·28	3·92	3·89
Ce_2O_3 ...	1·05				(La,Nd)	0·45		
Fe_2O_3 ...	1·43	—	0·24	—	Ce ...	0·06		
CaO	1·55	5·4	—	—	Fe ...	0·17	0·03	—
P_2O_5 ...	31·10	28·4	30·20	31·15	Ca ...	0·26	—	—
H_2O	15·29	14·9	16·42	15·96	PO_4 ...	4·08	4	4
insol. ...	—	—	0·38	0·23	H_2O ...	7·91	8·57	8·08
	99·78	103·3	99·71	100·24	$\Sigma(+)$...	12·24	11·85	11·67
D_4^{20}	3·265	3·14	—	—	$\Sigma(-)$...	12·24	12·0	12·0

1. Churchite, Cornwall (B.M. 40636). Mean mol. wt. of yttria fraction 239·4, corresponding approx. with Yt_2O_3, 35·7, Er_2O_3 5·7 %.
2. Churchite, Cornwall. Anal. A. H. Church, 1865. Re-calculated from Church's weights on the assumption that his ceric oxide was essentially a trioxide, mainly of yttria, and using modern atomic weights.
3. Weinschenkite, Bavaria. F. Henrich, 1922. Mean mol. wt. of total rare-earths 251·8; corresponding approx. with Yt_2O_3 41·3, Er_2O_3 11·2 %.
4. Weinschenkite, Bavaria. F. Henrich, 1935. Mean mol. wt. of total rare-earths 248·1.

1a. Empirical unit-cell contents calculated from the analysis and density of col. 1, together with the unit-cell dimensions determined on the same specimen.

3a., 4a. Atomic ratios, calculated from the analyses of cols. 3 and 4, on a basis of $PO_4 = 4$. $\Sigma(+)$, sum of cationic charges; $\Sigma(-)$, sum of anionic charges.

in 1867, showed that this mineral is also essentially an yttrium phosphate, but in this case the principal accompanying element is neodymium, with smaller amounts of erbium and cerium and quite minor amounts of lanthanum and other rare-earths.

The isolated rare-earths (50·41 %) were divided into yttrium and cerium earths through the double sulphates with potassium, in the usual way. The yttria fraction was found (41·37%) to have a mean molecular weight of 239·4, and a solution of its sulphate gave a very distinct erbium absorption band at λ 525 mμ; if it were wholly yttria and erbia, there would be 35·7 % Yt_2O_3 and 5·7 % Er_2O_3. The cerium earths (9·04 %) were found to contain 1·05 % Ce_2O_3, determined volumetrically by the bismuthate method; the remaining 8 % appears to be principally Nd_2O_3, and a sulphate solution gave strong absorption

bands at λ 576 and 523 mμ. The mean molecular weight of the rare-earths as a whole was found to be approximately R_2O_3 252. The specific gravity of this churchite was found to be D_4^{20} 3·265.

X-ray powder photographs (fig. 1) of churchite from this specimen and of weinschenkite from a Bavarian specimen (B.M. 1925,637) are

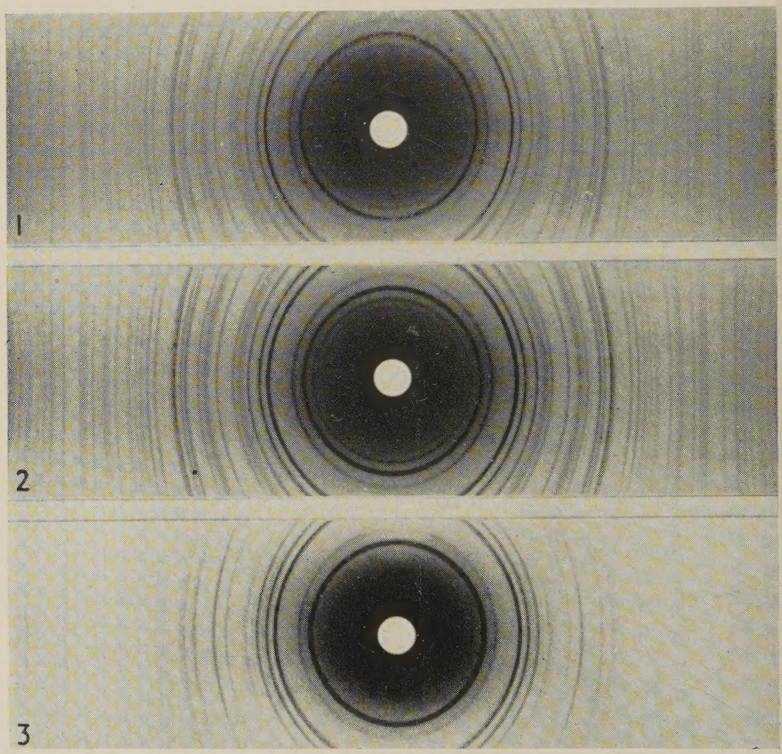

Fig. 1. X-ray powder photographs:

1. Churchite, Cornwall (B.M. 40635).
2. Weinschenkite, Auerbach, Bavaria (B.M. 1925,637).
3. Gypsum, 'Mosul marble'. (British Museum Research Laboratories.) [M.A. 12–190.]

6-cm. diameter camera. Co-$K\alpha$ radiation. Original photographs reduced from 4·5 to 4 inches wide.

an excellent match in spacings and intensities (table II). The empirical unit-cell contents shown in table I are calculated from the new analysis, specific gravity, and unit-cell dimensions (p. 215 and postscript) determined on the same specimen.

Morphologically the Cornish material consists of sub-parallel aggregates of platy crystals, and is quite unsuited for goniometrical study (as Church noted). The Bavarian material is better crystallized, and Laubmann was able to obtain goniometrical measurements; referred to the unit-cell with[1] a 5·60, b 15·11, c 6·18 kX, β 115·3°, the forms observed[2] are a (100), b (010), p (120), R (10$\bar{1}$), and (as a cleavage face)

TABLE II. X-ray powder data (Ångström units) for churchite.

1.		2.		1.		2.	
d.	Int.	*d.*	Int.	*d.*	Int.	*d.*	Int.
7·55	vs	7·50	vs	1·596	mw	1·600	mw
5·22	w	5·22	mw	1·557	vvw	1·560	vw
4·70	mw	4·70	m	1·539	vvw	1·535	vw
4·20	vvs	4·21	vvs	1·503	vw	1·499	vw b
3·74	ms	3·74	m	1·489	vw		
3·01	vs	3·02	vs	1·437	w	1·440	w
2·83	m	2·82	ms	1·408	vvw	1·410	vvw
2·61	mw	2·62	m	1·390	vw	1·397	w
2·52	vw	2·51	mw	—	—	1·374	vvw
2·47	vw	2·46	mw	1·344	w	1·438	w
2·44	vw	—	—	1·326	vvw	1·324	w b
2·37	w	2·39	mw	1·317	vvw		
2·162	mw	2·17	m	1·301	vw	1·306	w b
2·083	vvw	—	—	—	—	1·286	vvw
2·059	w	2.05	mw b	—	—	1·270	vvw
2·036	w			1·249	w	1·253	w
2·005	vvw	2·01	vvw	—	—	1·237	vvw
1·964	w	1·97	mw	1·216	w	1·222	w
1·927	vvw	1·94	vvw	1·197	vvw	1·201	vw
1·855	mw	1·861	m	1·180	vvw	1·186	vw
1·820	w	1·825	mw			1·176	vvw
1·773	m	1·776	m	1·160	vvw b	1·163	vw b
1·755	mw	1·755	w	1·139	vw	1·147	vvw
1·689	vvw	1·692	vvw	1·125	vvw	1·123	mw b
1·640	mw	1·643	mw	1·118	mw		

Order of intensities: vvs, vs, s, ms, m, mw, w, vw, vvw. b indicates broad line.

1. Weinschenkite, Nitzelbuch mine, Auerbach, Oberpfalz, Bavaria (B.M. 1925, 637), cobalt-$K\alpha$ radiation.
2. Churchite, Cornwall (B.M. 40335), copper-$K\alpha$ radiation.

c (001); Laubmann measured bp 54° 40′, aR 47°, ac 67°, which, considering the difficult nature of the material, agree reasonably well with the calculated angles bp 56·2°, aR 53·2°, ac 64·7°. The morphological data given in Dana (Syst. Min., 7th edit., p. 771) for weinschenkite are

[1] Re-determined on B.M. 40626. H. Strunz's figures yield by the transformation $\|\bar{1}0\bar{1}/0\bar{1}0/001\|$, a 5·46, b 15·12, c 6·28 kX, 113° 24′.

[2] Transformation Laubmann to present settings: $\|20\bar{2}/0\bar{1}0/00\bar{2}\|$.

inaccurate: the β angle cited on p. 771 does not correspond to the adopted setting and axial ratio, but to Strunz's X-ray setting, the correct value being β 113° 24′, as given on page 772; the cited ρ-value for u ($\bar{1}01$) is in consequence incorrect, while the prism observed by Laubmann is not (110) but (120) in the adopted setting, corresponding to the common prism of gypsum, which is also (120) in this setting. Laubmann observed an imperfect cleavage parallel to c (001), and a cleavage parallel to [001]; it is probable that this latter was parallel to b (010). It is also possible that some of Laubmann's terminal faces, R ($\bar{1}01$)—his c (001)—were cleavage faces. Church observed three cleavages, a very perfect one parallel to the terminal faces of the prisms, one parallel to the composition planes of the crystal-sheaves, and a third at right angles to the second and inclined to the first. These reports are in good agreement, and indicate that churchite has three cleavages parallel to a (100), b (010), and c (001). Of the isostructural minerals, gypsum has cleavages b (010), a (100), and n (011); brushite b (010) and c (001); and pharmacolite b (010).

The Cornish churchite is not well adapted to optical study owing to the difficulty of isolating single-crystal fragments from the sub-parallel aggregates, but a small single-crystal plate was mounted, orientated by an X-ray oscillation photograph and then examined optically. The crystals prove to be sub-parallel aggregates of plates parallel to a (100), and show an excellent cleavage parallel to b (010), in agreement with Church's observations. On a (100) extinction is straight and the positive acute bisectrix of an optic figure of small angle appears to be just outside the field of the microscope; on b (010) extinction is at 31° to the trace of (100). The observed refractive indices are included in table III. The optic orientation given by E. S. Larsen[1] is difficult to reconcile with these observations, and has therefore been disregarded.

Churchite and weinschenkite are clearly identical; the small differences in neodymium and yttrium content between material from Cornwall, Bavaria, and Virginia are insufficient to warrant even a varietal distinction. The name churchite has priority, and in our opinion the error in the original description, by which the yttria earths were overlooked, is not a sufficient reason to reject this name in favour of weinschenkite, especially as the latter name has also been used for quite a different mineral.

[1] E. S. Larsen, The microscopic determination of nonopaque minerals. Bull. U.S. Geol. Surv., 1921, no. 679, pp. 58, 168, 217; 2nd edit. by E. S. Larsen and H. Berman, ibid., 1934, no. 848, pp. 72, 113.

Finally, we may note that the interpretation of Church's original analysis presents some difficulties. There are no obvious sources of probable serious error in the analytical methods described, yet the

TABLE III. Optical data for churchite.

	α.	β.	γ.	2V.	Orientation.
1.	>1·58	—	<1·63	Moderate, positive	$\alpha \parallel [010]$, $\gamma : [001] = 28°$ in acute angle β.
2.	1·605	1·612	1·645	— positive	$\alpha \parallel [010]$, $\gamma : [001] = 35°$ strong dispersion of bisectrices.
3.	1·600	1·608	1·645	Medium, positive	$\alpha \parallel [010]$, $\gamma : [001] = 30°$ approx.
4.	1·620	1·620	1·654	Very small, positive	
5.	1·623	1·631	1·657	Small, positive	$\gamma : [001] = 31°$.

1. Weinschenkite, Bavaria. H. Laubmann, 1923.
2. Weinschenkite, Virginia. C. Milton, K. J. Murata, and M. M. Knechtel, 1944.
3. Weinschenkite, Bavaria. E. S. Larsen and H. Berman, Bull. U.S. Geol. Surv., 1934, no. 848, 2nd edit., p. 111.
4. Churchite, Cornwall. E. S. Larsen, 1921.
5. Churchite, Cornwall (B.M. 40636).

phosphate is seriously low compared with the total bases, while the summation is notably high. Even deducting the excess over 100 % from the bases, the ratio of bases to phosphate remains high with any probable mean molecular weight for the rare-earths. The specimens in the British Museum collection agree exactly with Church's description, consisting of a crust of sub-parallel aggregates of minute crystal plates on quartz, and there does not seem to be any more basic mineral present (such as pseudowavellite or an analogue of florencite) that might account for the low phosphate.

Note added in proof.—Because of some remaining uncertainty of the optical orientation of the Cornish crystals the cell dimensions were re-determined by Weissenberg and rotation photographs on morphologically and optically orientated crystals. The cell dimensions (p. 215) differ appreciably from those of Strunz. The X-ray photographs showed the following systematic absences: hkl only with $k+l$ even, $h0l$ only with h even. These lead to the space-group C_{2h}^6 in the orientation A2/a, or C_s^4 in the orientation Aa. The former is the space-group of gypsum.

Some data on synthetic aluminous and other pyroxenes.

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[Read January 11, 1951.]

ALTHOUGH detailed experimental investigations have been carried out on the lime, magnesia, and ferrous pyroxenes, relatively little attention has been devoted to synthetic studies of the group involving replacements by ions of higher valencies. In the present study determinations have been carried out on the limits of solid solution of alumina in pyroxenes in the system $CaSiO_3$–$MgSiO_3$–Al_2O_3. Determinations of the solubility of ferric oxide and titania in diopside were also made.

Experimental procedure.

Pure calcium carbonate, magnesia, silica (crushed and washed rock-crystal), alumina, ferric oxide, and titania were used for the preparation of the mixtures. The constituents in their requisite proportions were fused together four or five times with intervening crushing of the quenched glass. The product was an homogeneous glass free from crystalline material. Homogeneity and composition were checked by refractive index observations under the microscope. These have been plotted in figs. 1 and 2. Fig. 1 shows the effect of added alumina, ferric oxide, and titania (wt. %) on the refractive index of diopside glass, and fig. 2 indicates the variation in refractive indices of glasses in the system $CaSiO_3$–$MgSiO_3$–Al_2O_3.

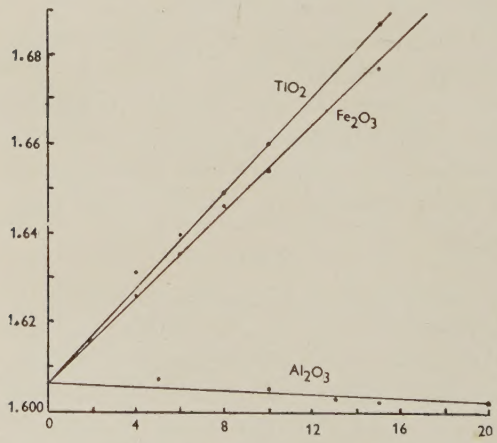

Fig. 1. Graph of refractive indices against composition of diopside glasses containing other oxides.

[1] Now at Division of Industrial Chemistry, Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia.

To determine the limits of solid solution, the glasses were crystallized by heating below their solidus temperatures for periods varying from two hours to several days. The shorter periods were generally sufficient for complete crystallization. If the product was in the solid-solution field, only one phase would be visible under the microscope. If it was outside the field, a second, generally crystalline, phase would appear. In some cases, several days' heating was insufficient to crystallize the glass completely. This happened with some of the more aluminous glasses and was taken as evidence of inhomogeneity. X-ray powder photographs were also used as a check on homogeneity, but were not as sensitive as microscopic examination.

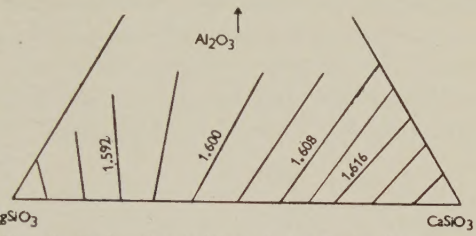

FIG. 2. Refractive indices of glasses in the system $CaSiO_3$–$MgSiO_3$–Al_2O_3. Lines at intervals of 0·004 of refractive index.

EXPERIMENTAL RESULTS.

High magnification showed that the crystallized products were either granular or fibrous in structure. In the latter case, with compositions lying outside of the solid-solution field, the second phase formed in parallel growth with the pyroxene.

The result of this microscopic examination is shown in fig. 3. The area within the curve represents the solid-solution limits of alumina in the pyroxenes in the system $CaSiO_3$–$MgSiO_3$–Al_2O_3. Glasses with compositions lying in this area will crystallize as a single pyroxene phase at temperatures below their solidus. The most precise determinations were made in the area close to diopside. Three series of compositions were prepared along lines joining diopside to alumina, and to the compositions represented by 'MAS' and 'CAS'.[1] The limits of solid solution along these lines were placed at:[2]

Diopside	87%	Al_2O_3	13%
,,	75	CAS	25
,,	80	MAS	20

[1] For the sake of simplicity in more complex formulae, the following abbreviations have sometimes been used in this paper: C = CaO, A = Al_2O_3, M = MgO, S = SiO_2.

[2] A. I. Zvetkov, Mém. Soc. Russe Min., 1945, ser. 2, vol. 74, pp. 215–222 [M.A. **11**–92] has reported mixed crystals on the join diopside-$CaAl_2SiO_6$ containing up to 18–19 wt. % Al_2O_3.

Away from this area the solubility of alumina fell off rapidly to about 5 % along the main part of the diopside–clinoenstatite series. The data in this part of the series is not as precise, owing to the high melting points, which caused some difficulties in the preparation of satisfactory glasses. The presence of minute air bubbles and vesicles also added to the difficulties of determination of homogeneity. Clinoenstatite glasses containing 5 % and 2·5 % Al_2O_3 were, however, prepared. When

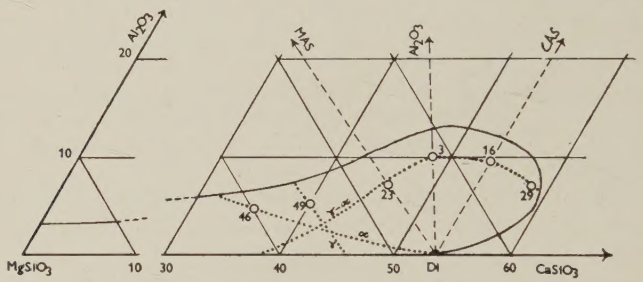

Fig. 3. Pyroxene solid solutions in the system $CaSiO_3$–$MgSiO_3$–Al_2O_3. Glasses within the curved line crystallize as a single phase. Dotted lines show refractive indices α 1·664, γ 1·690, and birefringence $\gamma-\alpha$ 0·025.

crystallized, the former was inhomogeneous, while the latter was almost quite homogeneous. A small lowering of the refractive index of the crystals also confirmed that the clinoenstatite was taking some alumina into solid solution. At the other end of the solid-solution area may be noted the small part beyond the diopside–CAS join. Here, there must be a small excess of the large calcium ion in the structure.

A few determinations were also made of the limits of solid solution of ferric oxide and titania in diopside. Glasses were prepared at 2 % intervals along the diopside–oxide join to the limit of 10 % of each oxide, and a further glass with 15 % of Fe_2O_3. These were then subjected to the same treatment as the aluminous mixtures. In this manner the limits for homogeneous crystallization in the two cases were found to be diopside 94 % with titania 6 %, and diopside 90 % with Fe_2O_3 10 %. Larger, although inhomogeneous crystals were obtained by slow cooling from the melt. These were useful for the qualitative determination of the effect of the various oxides on the optic axial angle, extinction, and dispersion.

Optical properties of the artificial pyroxenes.

The refractive indices and other properties are summarized in table I. Refractive indices were measured on fine material obtained by the

crystallization of glasses. The optic axial angles and extinction angles were measured on ground mounts of coarse inhomogeneous crystals obtained by slow cooling from the melt. The optic axial angle was determined with the universal stage.

TABLE I. Optical properties of pyroxene solid solutions.

Aluminous:

No.[1]	Composition. $CaSiO_3$.	$MgSiO_3$.	Al_2O_3.	α.	γ.	$\gamma-\alpha$.
3	48·3	41·7	10·0 %	1·668	1·693	0·025
16	53·5	37·0	9·5	1·669	1·694	0·025
23	45·6	46·9	7·5	1·669	1·695	0·026
29	58·5	34·5	7·0	1·670	1·695	0·025
46	35·0	60·0	5·0	1·664	1·682	0·018
49	40·0	55·0	5·0	1·667	1·690	0·023
Diopside (artificial)				1·664	1·694	0·030

Ferriferous:

	Diopside.	Fe_2O_3.			
F1	98·0	2·0 %	1·670	1·702	0·032
F2	96·0	4·0	1·677	1·705	0·028
F3	94·0	6·0	1·684	1·710	0·027
F4	92·0	8·0	1·691	1·716	0·025

Titaniferous:

	Diopside.	TiO_2.			
T1	98·0	2·0 %	1·667	1·695	0·028
T2	96·0	4·0	1·677	1·704	0·027

Optic axial angle on coarse material:

Aluminous	76°
Ferriferous	77
Titaniferous	77

Maximum extinction angle on longitudinal section:

Aluminous	43°
Ferriferous	43

[1] Compositions 3–49 plotted in fig. 3.

Diopsides containing alumina.—On the whole, this constituent has very little effect on the optical properties of diopside. The α refractive index is slightly raised, while γ is unaffected, the net result being to decrease the birefringence by about 0·005 in the highly aluminous members. The birefringence of pure diopside is 0·030; this is lowered to 0·025 by the addition of about 10 % alumina. In contrast to this, alumina lowers slightly the refractive index of the corresponding glass. In fig. 3 the pyroxenes with a birefringence of 0·025 are indicated by

a dotted line. There was little change in the extinction angle, but there was an increase of about 16° in the optic axial angle. It is evident that alumina does not cause any characteristic change in the optical properties by which its presence could be accurately diagnosed or determined quantitatively.

Diopsides containing titania.—The effect of titania is more marked than that of alumina. The refractive indices of diopside are increased by about 0·004 for each per cent. of TiO_2, and at the same time there is a similar decrease in the birefringence, as was seen in the aluminous pyroxenes. The optic axial angle was increased to about 77°. This is of particular interest because it has been suggested that titanium causes a considerable drop in the optic angle measurement. The above result is direct evidence that TiO_2 cannot be the cause of low optic axial angle in some titaniferous pyroxenes. The synthetic material is colourless.

Diopsides containing ferric oxide.—The changes in optical properties were similar to those noticed with titania. The refractive indices were increased. γ increases about 0·003 for each per cent. of Fe_2O_3, α at a slightly greater rate, so that there is a decrease of about 0·005 in the birefringence of the members rich in iron. The optic axial angle was increased to about 77°. The colour of the iron-rich members is striking —a strong orange-brown in section. The preparation with only 2 % Fe_2O_3 had only a slight greenish tint under the microscope. All varieties were practically non-pleochroic. The dispersion was strong $r > v$, and was striking in near optic axis sections.

Structural replacement in the pyroxenes.

B. E. Warren and J. Biscoe (1931) suggested as a general formula for pyroxenes $X_m Y_{2-m}(Si,Al)_2(O,OH,F)_6$, where m tends to be unity or zero, and as much as one quarter of the silicon may be replaced by aluminium. In this formula X = Ca, Na, K, or Mn, and Y = Mg, Fe, Al, Ti, or Mn. In simple pyroxenes there is no difficulty in placing the various elements in their respective places in the structure. Divalent elements should replace each other in the X and Y groups according to their ionic radii. Alkalis should go into the X group and the valencies balanced by the replacement of divalent elements in the Y group by aluminium or ferric iron as in the jadeite and acmite molecules. The position becomes more complex, however, if the latter oxides are present and alkalis are not, as is the case with these synthetic materials and also with many natural

minerals. The three replacements in the synthetic materials will be now considered.

Alumina. Although the ionic radius of aluminium (0·57 Å.) is greater than that of silicon, it can replace the latter in the oxygen tetrahedron as is well known in the felspar structure. When diopside, therefore, takes alumina into solid solution, the valencies are balanced by half of the new constituent going into the *Y* group to replace magnesium (ionic radius 0·78 Å.), and the other half in with the silicon group. The overall result should be a small decrease in cell size. The introduction of the larger aluminium ion into the rigid oxygen tetrahedron should not affect this part of the structure, while the replacement of magnesium by aluminium in the more loosely bound part of the structure should tend to cause a slight decrease in the cell dimensions. This result was shown by a series of powder photographs of diopside alumina mixtures. With increase in alumina content an increase in the line spacings denoting a decrease in cell size was evident on visual inspection.

Ferric oxide.—The same remarks may be applied to this constituent as were applied to alumina. The ferric ion should in part replace silicon, and in part the *Y*-group metal, in this case magnesium. There can be little objection to the replacement of silicon by the ferric ion, as its ionic radius (0·67 Å.) is only a little greater than that of aluminium. The limit of solid solution should therefore be more restricted; and this has been confirmed by synthetic work. The ferric and magnesium ions are of similar size, so that powder photographs of iron-rich synthetic diopsides showed no alteration in cell size. That the ferric ion can enter into the oxygen tetrahedron has been shown by G. T. Faust (1936), who proved the existence of the iron-orthoclase molecule.

Titania.—The position which titanium takes up in any structure depends upon the valence of that particular titanium ion. In natural minerals titanium is usually reported as the dioxide TiO_2, although E. Dittler (1929) suggests that it may sometimes occur as Ti_2O_3. He was able, under suitable conditions, to prepare synthetic silicates and other compounds in which trivalent titanium occurred. It is unlikely, however, that such conditions could ever occur in nature. This is especially so in the case of pyroxenes, because those which are rich in titanium are also rich in ferric oxide. That Fe_2O_3 and Ti_2O_3 could coexist under any conditions of elevated temperature is most improbable. It can be safely assumed that the dioxide is present in pyroxenes, and can as such replace silica to a small extent. The synthetic work showed

this limit to be about 6 %, which is comparable to the amount of ferric iron which enters into the oxygen tetrahedron (half the total amount of Fe_2O_3 soluble in diopside, which was determined as 10 %). This also follows from the similar ionic sizes of titanium and trivalent iron. Furthermore, no increase in cell size can be expected and the powder photographs showed no change.

Similar conclusions were reached by T. F. W. Barth (1931), who obtained comparable results with some synthetic work. He held preparations of 94 % $CaMgSi_2O_6$ with 6 % $CaMgTi_2O_6$ and of 90% $CaMgSi_2O_6$ with 10 % $CaMgTi_2O_6$ at 1300° C. for two hours and obtained homogeneous crystals. The latter composition contains about 6 % TiO_2, thus being in agreement with the present results. In all these artificial materials, titanium must occur in the silicon group although in natural pyroxenes rich in alumina it may preferably replace magnesium, the valence being balanced by the replacement of silicon by aluminium.

Natural pyroxenes rich in alumina, ferric oxide, and titania.

Pyroxene analyses are common in the literature, and a large number of the igneous varieties have been collected and published in tables by P. Niggli (1943). These constitute the majority of the reliable analyses of igneous pyroxenes. Metamorphic pyroxenes are less common. In this work, interest is centred on those which have a low alkali content; 76 such analyses, taken chiefly from Niggli's tables, together with a number of metamorphic pyroxenes (C. E. Tilley, 1938), have been recalculated as percentages of $CaSiO_3$, $(Mg,Fe,Mn)SiO_3$, and $(Al,Fe)_2O_3.TiO_2$. Fig. 4 shows a plot of these analyses on a diagram corresponding to fig. 3. Most of the natural minerals lie within the experimental field, and a survey of those lying outside the field shows that these are titania rich. If the titania were subtracted from the total $Al_2O_3+Fe_2O_3+TiO_2$ and added in with the silica, these analyses would fall within the synthetic curve. The one or two exceptions to this will be mentioned below.

Two theoretical probabilities which could be drawn from the above experimental results are confirmed by the plot of analyses in fig. 4. They are, firstly, that the total of alumina + ferric oxide in a pyroxene is unlikely to exceed the maximum amount of solid solution possible for alumina itself, and, secondly, that this limit will not be appreciably affected by ferrous oxide replacing magnesia. Many of the pyroxenes

plotted in fig. 4 are rich in FeO. Titania may be able to increase the total amount of high valence oxides as its replacement of silica is of a somewhat different type.

There are several published analyses which do not agree with the above results. In each case there are unusual factors, but without further study no decisive conclusions can be reached. The most notable

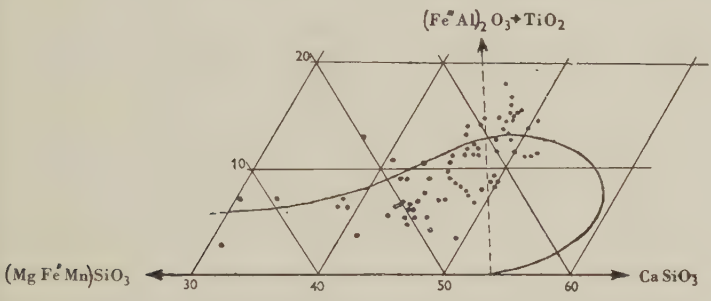

FIG. 4. Curve of fig. 3 and 76 natural pyroxenes in part of the triangle $CaSiO_3$–$(Mg,Fe,Mn)SiO_3$–$(Fe,Al)_2O_3+TiO_2$. (Pyroxenes with low $(Fe,Al)_2O_3+TiO_2$ not plotted.)

examples are the titanaugite from Aberdeenshire with over 24 % $Al_2O_3+Fe_2O_3+TiO_2$ which is uniaxial (B. E. Dixon and W. Q. Kennedy, 1933), an augite from Cap Tourmente, Quebec, with 24 % $(Al,Fe)_2O_3$ and little titania (H. M. Putman, 1942), a titanaugite from Siberia with 8·97 % TiO_2 (P. I. Lebydev and A. P. Lebydev, 1934), and two peculiar pyroxenes obtained from artificial rock melts (J. Morozewicz, 1898), one of which contains over 39 % $Al_2O_3+Fe_2O_3+TiO_2$.

The optical properties of the artificial materials did not show any significant changes which might be used for identification purposes. A comparison with analysed natural pyroxenes is in harmony with this. Of the group of minerals with which this work is concerned, there is no consistent change of properties which could not be attributed to changes caused by replacements among the divalent elements. The decrease in birefringence noticed in the synthetic pyroxenes is reflected in the natural minerals. This seems to be a characteristic effect of the entrance of Fe_2O_3, Al_2O_3, and TiO_2, and has been confirmed by H. H. Hess (1949). This particularly applies to alumina, which causes no appreciable change in properties. Mauve-coloured pyroxenes are often referred to as titanaugites, but not all proved titaniferous augites are of this colour.

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An investigation of high-temperature optics in some naturally occurring plagioclases.

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Introduction.

FOR several years now it has been generally appreciated that plagioclase felspar formed at high temperature differs optically from that formed at lower temperatures. Much of the evidence for this has been provided by the Austrian workers, notably Köhler (1–3), Scholler (4), and Tertsch (5–7), who have prepared revised curves to supplement the universal-stage stereograms of Reichert (which are for use with low-temperature material). There are a number of interesting petrological points which have not yet been fully investigated. Much work has been done on synthetic material, and it is not clear to what extent the high-temperature forms occur naturally. There may be two distinct and separate types of plagioclase structure, or the two forms may grade into one another. It may be possible to explain the optical anomalies as an order-disorder phenomenon; a more disordered state has been 'frozen-in' in those felspars which have formed at a high temperature and cooled rapidly. A more detailed understanding of the conditions required for the production of high-temperature optics would be a useful aid in questions of petrogenesis.

The present work was undertaken in the hope of obtaining further information on some of these points. The plagioclase-bearing rocks selected were of a variety of types and included some in which it appeared reasonable to expect high-temperature felspars. The plagioclase in each rock was studied in detail using universal-stage and refractive-index methods and the results obtained were compared.

It is not proposed to give here an exhaustive survey of earlier work in this field, merely to comment on some of the more important aspects. Useful surveys of the methods and conclusions of the Austrian workers have been given by Köhler (3) and, more recently, by Reynolds (8), who also provides a valuable bibliography. The use of drastic heat-treatment to produce high-temperature optics in plagioclase has been tried by

Barth (9) and Barber (10) with varying success. Oftedahl (11, 12) and Barth (13) have done much work on plagioclases found in the rocks of the Oslo igneous complex in testing the results of the Austrian workers. Their results agree partially, but not completely, with the high-temperature curves of Köhler, and they postulate an intermediate transition series between the high- and low-temperature plagioclases—the position of any one crystal depending on the rate of cooling as well as the temperature of formation. In addition, they checked the universal-stage results against refractive-index determinations and found that for high-temperature felspar the universal-stage values were consistently higher in anorthite than the refractive-index values. Rhomb-porphyry plagioclase phenocrysts had universal-stage results 7–9 % higher in anorthite content, while a phenocryst from a basalt gave 61 % An compared with the 48 % found by refractive-index determinations. Köhler (1949) also reported that the standard Reichert curves, when used with high-temperature plagioclase, gave an An content 10–15 % too high.

The plagioclase phenocrysts of some Hekla lavas have been investigated by H. Sørensen (14), who found that some felspars in the devitrified lavas had cores with high-temperature optics and an outer, more calcic zone, with low-temperature optics. Some divergence from Köhler's curves is attributed to a difference in composition between adjoining twin individuals. Turner (15, p. 397) also reports 'A discrepancy between the values for composition as determined [by universal-stage measurements] in different pairs of subindividuals belonging to a single crystal . . . is by no means uncommon'. This anomaly has been observed by other workers and appeared again in the course of this investigation; it is most readily interpreted as a difference in composition between the two subindividuals. Köhler's method of plotting cannot be expected to give accurate results in such cases.

Source of material.

The object of the study was the natural occurrence of high-temperature plagioclase. Six specimens from the collection at King's College were selected for investigation. Porphyritic pitchstones were thought to be a likely source for such felspars and three were selected, two from Arran and one from Tenerife. Other rocks, expected to carry low-temperature material, were investigated at the same time. These were an olivine-gabbro (Stonehead, Aberdeen), a hornblende-pegmatite (Ronez, north Jersey), and a leuconorite (Bushveld complex, South Africa). The rock

types are described briefly below and the plagioclase they contain is commented on in rather more detail.

Universal-stage measurements.

The universal stage used was the Leitz 4-axis model, and the technique for the determination of the plagioclases was broadly that given by Reinhard (17). Each crystal was measured at more than one point – where possible on two or more adjoining twin individuals. Albite (or more rarely, pericline) twin lamellae were present in all the felspars, and the position of the composition plane of the twin lamellae was measured directly for each crystal. It was not possible to use the cleavage traces as a second reference plane, since the cleavage was very variable—excellent in the leuconorite, for example, but not visible in the hornblende-pegmatite. The cleavage was also poor in the pitchstone plagioclases: it is possible that good or bad cleavage, which appears consistent for all the slides made from one rock specimen, is in some way related to the homogeneity of the crystal—or possibly to the thermal history.

In the cases where two adjoining twin individuals were measured it was also possible to determine the anorthite content from the twinning relationship between them: this provided a useful check on the value obtained from the direct measurement of the composition plane. Any results where the stereographic plot showed a divergence of 2 or more degrees from the 90° relationship between the optic planes were discarded. It was interesting to note that many of these inaccurate measurements had one feature in common: the optic axial plane, which was measured directly, was so placed that the two optic axes were lying at 25° or more from the vertical. It appears that it is difficult to measure an optic axial plane in this position accurately, presumably because the optic axes obscure the true extinction position.

The results of measurements made on a number of crystals are shown in each of the composite stereograms (figs. 1–6). The stereogram curves are taken from those prepared by Reinhard (17). Selected parts of his tables 2 and 5 have been combined: n_β is always in the centre of the stereogram, and in each case the continuous curves refer to the poles of normal 'parallel' twins and to the cleavage directions; the broken lines refer to the poles of 'edge' twins.

Olivine-gabbro, Stonehead, Aberdeen.—This is a familiar rock-type which is used as part of a teaching collection. The minerals present include a ragged red-brown mica, augite, abundant olivine, colourless apatite, and iron-ore. The olivine shows partial but limited alteration;

some of the augite crystals have regularly arranged rod-like inclusions in two directions. The plagioclase is in fresh condition and has good cleavage. The crystals may be composite and intergrown, with irregular edges and varied twinning. Pericline is much less common than albite twinning. The multiple-twin lamellae are often very broad; in some cases the lamellae extend only part of the way along the crystal and may taper to a finish—making an accurate determination of the composition plane very difficult. No regular zoning was observed, but the extinction in some crystals is rather patchy.

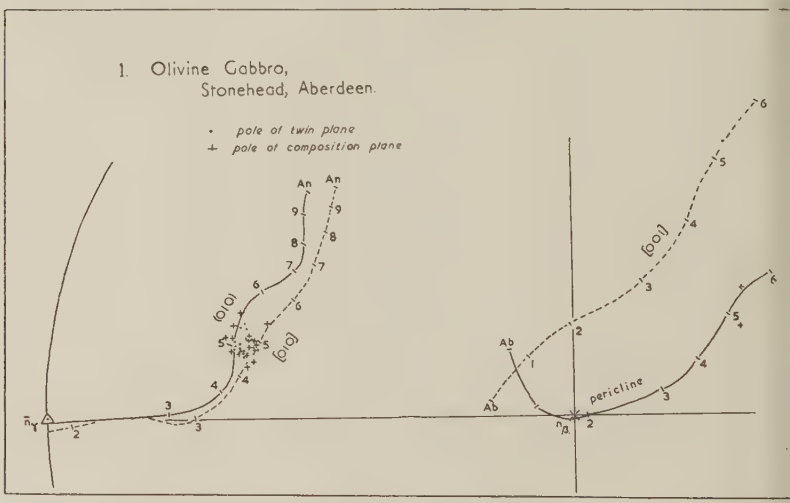

Fig. 1. Composite stereogram of plagioclase from olivine-gabbro, Stonehead, Aberdeen.

The composite stereogram (fig. 1) shows mainly albite twinning. The poles of the twin planes are less scattered than those of the composition planes: this is to be expected, since the position of the composition plane is determined by a single, possibly inaccurate, measurement, while the twin plane is found as a relationship between two separately-measured crystal individuals so that individual errors of measurement will have less effect. The plagioclase shows little variation in composition, 5 6 % only, and this homogeneity is confirmed by the other measurements on pericline and (001) twinning. The small displacement to one side of the (010) curve appears to be systematic rather than random, but the cause of this is not known. In other respects this is a normal low-temperature mineral, with little variation either in optics or composition.

Hornblende-pegmatite, Ronez, north Jersey.—An unusual type of rock of uncertain antecedents, but probably formed at a low (pegmatitic) temperature. It is coarsely crystalline and formed principally of hornblende and plagioclase with subordinate amounts of quartz, apatite, zircon, and iron-ore. The quartz is interstitial. Partial alteration of hornblende to pennine is common and the pennine is often spherulitic. Crystal boundaries are irregular and intergrown. There are clearly two

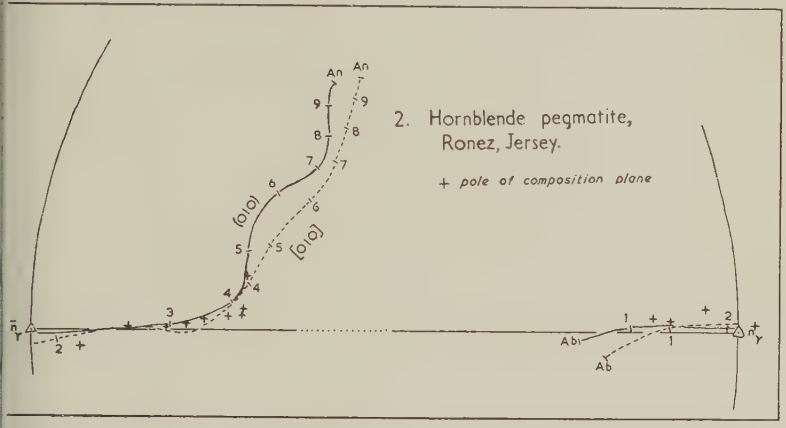

Fig. 2. Composite stereogram of plagioclase from hornblende-pegmatite, Ronez, Jersey.

hornblendes: an earlier-formed red-brown hornblende forms the cores of the crystals, and a later, marginal, pale-green mineral is in optical continuity with it. The brown hornblende has opaque relic inclusions regularly spaced at an oblique angle to the cleavage. Plagioclase occurs as large simple crystals, often partially or almost wholly decomposed; in some cases there is a selectively altered core. The most striking feature of the felspars is the strongly marked simple zoning—the so-called normal zoning with a core more basic than the margin of the crystal. Cleavage was not visible in the sections prepared.

Albite twinning is common, but only one set of the twin lamellae is broad enough for the optics to be measured accurately. The lamellae may extend only part of the way along the crystal. Twinning on other laws, such as Carlsbad, does occur, but is uncommon, and the universal-stage measurements had to be confined to the composition planes of the albite twins (fig. 2). A single measurement like this can lead to ambiguous results in plagioclase with low anorthite content. This ambiguity has

been overcome as far as possible, firstly by comparative refractive-index measurements and secondly by measuring at several points across the crystal. Since the zoning is continuous, not oscillatory, the combined series of results can generally be interpreted in only one way. As shown in the stereogram, the range in composition is large, more than 30 % An the variation measured in a single crystal is 16 % An. Zoned crystal

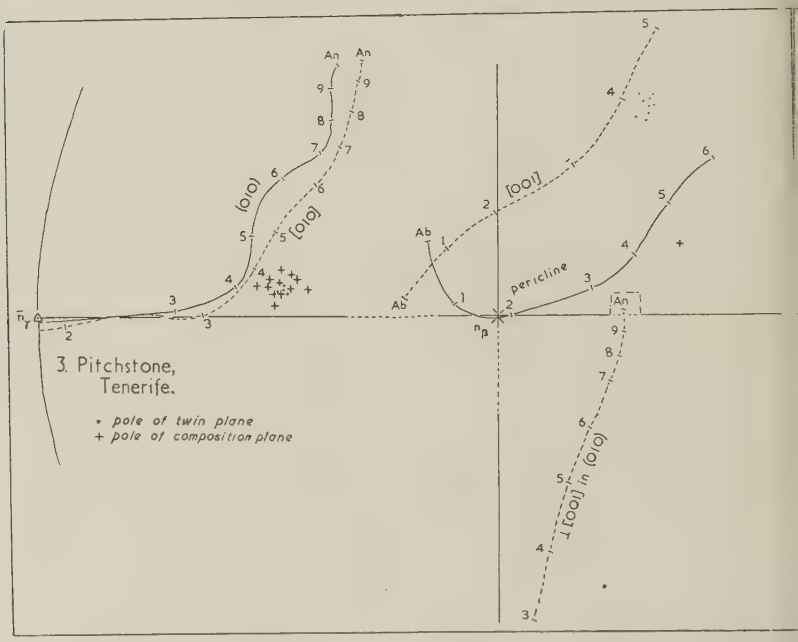

FIG. 3. Composite stereogram of plagioclase from porphyritic pitchstone, Tenerife.

are difficult to measure accurately and the (010) composition-plane poles approximate as closely to the low-temperature curve as could be expected. The evidence in favour of these plagioclases being formed at a low temperature is consistent with the coarse-textured pegmatitic facies in which they occur.

Porphyritic pitchstone, Tenerife.—The pitchstone has a micro-crystalline groundmass with many isotropic patches and some iron-rich segregations. Phenocrysts other than plagioclase include an idiomorphic hornblende and a clinopyroxene often intergrown with iron-ore. The plagioclase is in two generations: in addition to the large phenocrysts there are numerous tiny lath-like crystals scattered throughout the mass

and fluxionally arranged. The large phenocrysts are also lath-shaped, and elongated parallel to [010]. They are sometimes composite, and although fresh have many small inclusions. Cleavage was not seen in the prepared sections. The larger twin individuals have a somewhat patchy extinction suggesting that the composition is not quite uniform; regular concentric zoning was not observed. The phenocrysts show both single and repeated twinning, mainly parallel to the direction of elongation. The albite twin lamellae are often very narrow, may extend only part of the way down the length of the crystal and terminate irregularly. The twinning is sometimes complex, in several directions within a single crystal. The composite stereogram (fig. 3) for this plagioclase is considered together with that for the Glen Cloy felsite felspar.

Porphyritic felsite, Glen Cloy, Arran.—The matrix, which was once spherulitic, is now devitrified and difficult to interpret. The texture is variable and the groundmass may include considerable amounts of chlorite and calcite. There is some iron-ore present, but the only phenocrysts are of plagioclase and these often occur in groups. The plagioclase is badly decomposed, and there is much secondary development of calcite. The crystals were originally euhedral, mainly equidimensional, although some are lath-shaped; they show evidence of corrosion prior to decomposition. The size-range of phenocrysts is considerable. The albite twin lamellae are thin and not very numerous. There is some zoning, mainly from the centre to the margin of the crystals. It is difficult to interpret either the twinning or the zoning because of the decomposed nature of the crystals. Plagioclase also occurs as a mosaic of small crystals, with some groups in optical continuity.

The stereograms for Tenerife (fig. 3) and Glen Cloy (fig. 4) felspars have much in common and may be considered together. In both cases there is a systematic displacement from each of the three curves, (010), [001], and $\perp$[001] in (010). The composition of both plagioclases is about 40 % An and shows little variation. The displacement of the (010) twin-plane poles from the low-temperature curve is considerable, and is at least as great as that of the composition-plane pole (as with the other stereograms, the poles of the composition plane show greater scatter). Thus these two groups of plagioclase crystals, although markedly different in habit, show similar anomalous optics, due probably to a similar petrogenesis; whether these anomalies are the full high-temperature optics is discussed later.

Porphyritic pitchstone, Brodick, Arran.—This is one of the more attractive of the Arran pitchstones with many acicular and arborescent crystallites set in an isotropic matrix. The pale-green acicular crystallites are probably pyroxene. Phenocrysts are of quartz, plagioclase,

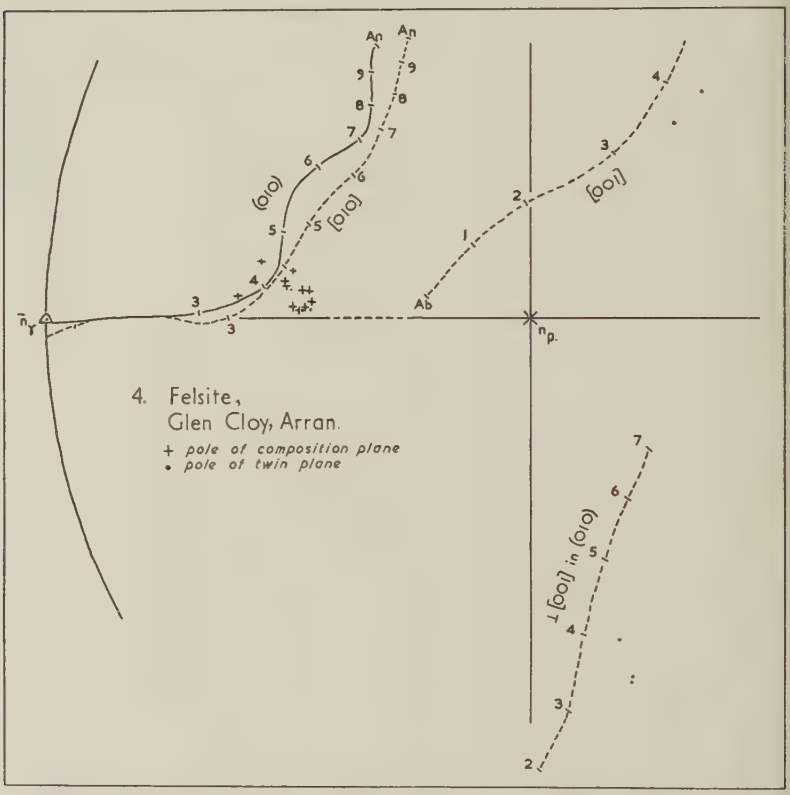

Fig. 4. Composite stereogram of plagioclase from porphyritic felsite, Glen Cloy, Arran.

and pyroxene; the pitchstone is known to carry olivine also, but this is not present in the sections prepared. The quartz phenocrysts were originally euhedral, but are now much corroded. Undulose or strain extinction is not conspicuous. A striking feature is the spherulitic fringe of large and small crystallites bordering each quartz crystal. Porphyritic pyroxene is much less abundant; the crystals are euhedral to subhedral, pale-green in colour and non-pleochroic. The plagioclase

phenocrysts are equidimensional and variable in size; they are sometimes grouped together in a unit of several unrelated crystals, or intergrown with pyroxene and iron-ore. The felspar crystals are euhedral, but may show some evidence of corrosion. Acicular crystallites form a fringe around the felspars which differs from the spherulitic fringe of the quartz phenocrysts, since here the crystallites are orientated at right

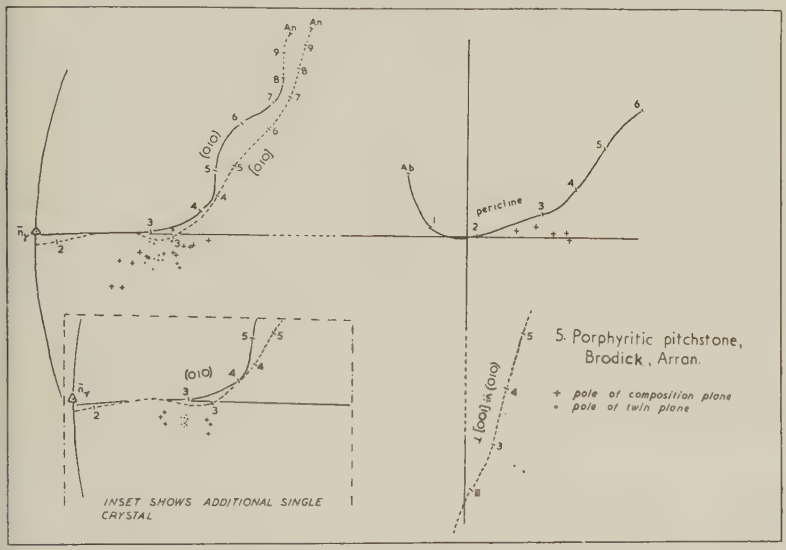

Fig. 5. Composite stereogram of plagioclase from porphyritic pitchstone, Brodick, Arran.

angles to the crystal edge. The twinning is often complex and the twin boundaries may be irregular. Individual twin bands tend to be rather broad and some crystals show a considerable patchiness under crossed nicols, a phenomenon that is perhaps too irregular to be satisfactorily termed zoning.

The plagioclase in this rock is more acid (An_{30}) than that of the other two pitchstones. The displacement from the normal curves (fig. 5) is in the same direction as it is in figs. 3 and 4. The most interesting feature is the way in which the composition shown by the twin-plane measurements on (010) is often intermediate between the values obtained from measurements on the composition plane of alternate albite twin lamellae. (This is well illustrated by the inset stereogram

of a single crystal.) If there is a difference in composition between adjoining twin lamellae, the determination of the twin plane between these adjacent individuals gives an anorthite value intermediate between that obtained for the two lamellae.

It is significant at this point to recall the recent X-ray work on the structure of the plagioclases (Cole, Sörum, and Taylor (18)). Here it was shown that the albite structure persists up to about An_{30} and the anorthite structure is stable above An_{72}. The intermediate plagioclases between these two limits of composition have a third type of structure consisting of alternating slabs of An-type lattice and Ab-type lattice. The intermediate structures are believed to be superlattices, and it is possible to disorder the structure by appropriate heat-treatment. The transition from the intermediate to the other structures may occur at some other composition value under different conditions of crystallization—it may not even be present for the high-temperature plagioclases. With this work in mind it is not difficult to appreciate that a felspar with a composition near one of these transition points may exhibit unusual features, particularly if cooled rapidly from a high temperature of formation. It may be, for example, that above a certain temperature the two types of structure form simultaneously. Thus at the albite-intermediate transition point, an albite-type structure (An $<$ 30) might form at the same time as an intermediate-type structure (An $>$ 30 %). With slow cooling the structure would be able to stabilize itself by some form of reorientation. If the cooling is rapid, as with a pitchstone, the differences may be 'frozen-in', and might be expected, as in the Brodick example, to have controlled to some extent the formation of the twin lamellae. The refractive-index measurements, discussed later, demonstrate that for these Brodick crystals, the alternating twin lamellae have compositions above and below about An_{20} rather than An_{30} %. This variation in composition between adjoining twin lamellae may prove, when better understood, to be useful for analysing the thermal history of plagioclases with a suitable anorthite content.

Leuconorite, Bushveld complex.—A rock formed of two minerals only, plagioclase and orthopyroxene, the former in considerable excess. The texture of the rock and the relationship between the two constituents have been discussed in a recent paper by Wells (16). The explanation proposed is essentially one of simultaneous crystallization with sometimes one mineral slightly in advance and sometimes the other. Both minerals have rounded and intergrown boundaries. The plagioclase is very fresh and has excellent cleavage. The crystals are intergrown but

not composite or complex. Twin planes are characteristically sharp and straight—only very occasionally are the boundaries irregular or tapering. The albite twin lamellae are broad, and adjoining twins can usually be measured. The plagioclase from this rock, with An_{70-80}, is more basic than the other material investigated. There was no particular

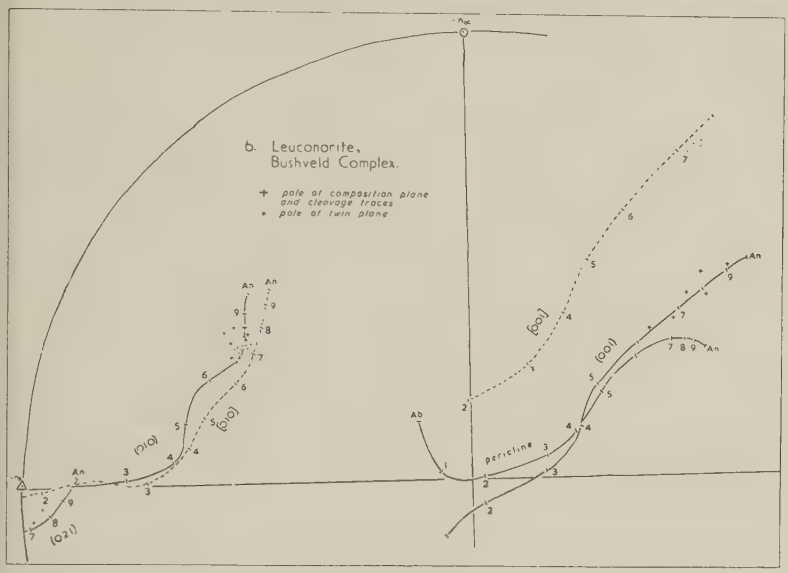

FIG. 6. Composite stereogram of plagioclase from leuconorite, Bushveld complex, South Africa.

reason to expect it to show high-temperature optics, but, on the other hand, the composition range includes the point where the second change in structure takes place: the X-ray work has shown the anorthite-type structure to be stable with more than An_{72}; with less anorthite the intermediate-type structure is formed.

The results obtained are not conclusive. It can be seen from the stereogram (fig. 6) that there is reasonably close agreement with the low-temperature curves. The (010) curve is much shortened towards the anorthite end, and although there is some evidence that the composition-plane readings show a greater variation in An than the twin-plane readings, the points are too crowded together for any differences to be significant. Results from the other curves are more interesting. The [001] values for the twin-plane curve can be compared with the (001) values for the cleavage: the former show only a 4 % variation in

composition; the latter about 25 %: the change in composition here is across a (001) twin plane, not as before an albite twin plane. It would be interesting to investigate high-temperature plagioclases with An_{75}, for on such evidence as is available it seems likely that they would show a similar inhomogeneity to that found towards the albite end of the series. Here again it might prove possible to deduce something of the thermal history of the rock from the composition variation in the crystal.

Refractive-index measurements.

The Norwegian workers reported that universal-stage measurements with high-temperature felspars gave incorrect anorthite percentages, and such measurements should clearly be checked by some other independent method. Since crystals from the same rocks may vary in composition, a chemical analysis—which is necessarily a bulk analysis of many crystals—was felt to be inadequate. Refractive-index measurements performed on single crystals are not open to the same objection. The method finally adopted used a thin section of slightly more than standard thickness (about 0·035 mm.). A suitable felspar—where possible one showing maximum birefringence—was then cut out of the section, and the extreme indices $n_{\alpha'}$ and $n_{\gamma'}$ were measured on a selected part of the crystal edge by the standard immersion technique. The crystal was then remounted and examined on the universal stage. This method has a number of disadvantages: the crystal tends to break up before it is remounted; a more serious objection is that refractive-index measurements are necessarily made on the crystal edge, while universal-stage measurements are made at some distance within the crystal. This must give rise to a discrepancy in any zoned crystal. A further source of error is in the extrapolation from the measured values $n_{\alpha'}$ and $n_{\gamma'}$ necessary to obtain the values for n_α and n_γ (or possibly n_β). The refractive-index variation diagram of Emmons (19) was used for extrapolation; the results are, of course, most accurate when n_α and n_γ are nearly in the horizontal plane of the crystal section—i.e. when the crystal shows maximum birefringence. Because of these complicating factors, it was thought sufficiently accurate to measure the refractive indices of the crystal in white light; the refractometer used was compensated to give the Na-light value. Each index was measured at least three times.

Table I compares the anorthite values found by the two methods. The composition has been calculated from the refractive indices using

both the empirical graph given by Chudoba (20) and the amended version proposed by Chayes (21), although to simplify the table the Chayes values are given only in the final column. The difference between the two sets of values is generally less than 2 %. The two curves diverge most over the albite range (An_{0-10}) and for the more basic felspars ($An > 60$). In this latter region Chayes has been able to incorporate new and much improved data. In dealing with the intermediate felspars he has had to rely more on results culled from the literature over the past fifty years. Those results that are clearly improbable have been rejected, but more really accurate determinations are still required. The correspondence between the two curves in this intermediate region may be due to the fact that many of the same determinations were used for both, and this part of Chudoba's graph may still require minor modifications.

The refractive indices measured are quoted to the fourth place. This is justified in view of the reproducibility of the measurements—it is one of the advantages of this method that determinations can be repeated on the same crystal as often as required—and the probable error (calculated on the standard square-root formula) was greater than 0·0003 in only 5 of the 58 determinations recorded here. This is not, of course, the same thing as claiming an absolute accuracy of this order, but, as conditions were standard throughout, the relative accuracy is adequate for purposes of comparison.

In the last column of the table the two sets of values are compared. In addition to the individual comparisons, the mean difference for the two methods for all the crystals from one rock is given. It is at once clear that the Brodick plagioclase is markedly different from the other material. The refractive-index results are consistently lower—as the Norwegians also found with high-temperature felspars—and this strongly supports the view that these are high-temperature forms. It is more difficult to explain why three of the other four rocks show a constant mean difference of about 4% An between the two sets of values. It seemed possible that this discrepancy might be inherent in the experimental method used—and this was, in fact, found to be the case. A number of refractive-index measurements were made on these felspars in white light and were repeated using Na-light. In all cases the white-light values were lower, the difference being equivalent to about 4–5 % anorthite (range 0·0022–0·0028). The selection of the end-point when matching crystal and liquid is of course more subject to personal factor when white light is used, but the extent of the variation is not

TABLE 1. Plagioclase composition determined by two optical methods.

The numbers in column 1 refer to the crystal and, in brackets, to the sub-individual measured.

		Refractive-index measurements						
		n_α.	% An.	n_β.	% An.	n_γ.	% An.	% An mean.
Olivine-gabbro, Stonehead, Aberdeen.	1 (1)	—	—	1·5566	49	1·5599	46·5	48
	3 (1)	1·5500	42·5	—	—	1·5594	45·5	44
	5 (1)	1·5526	47·5	—	—	1·5599	46·5	47
	6 (1)	1·5530	48	—	—	1·5605	48	48
	8 (1)	—	—	1·5545	44	1·5606	48	46
Hornblende-pegmatite, Ronez, Jersey.	1 (1)	1·5537	49	—	—	1·5635	53	51
	2 (1)	1·5517	45	—	—	1·5592	45	45
	2 (4)	1·5384	21	—	—	1·5452	19	20
	3 (1)	1·5342	14	—	—	1·5428	14	14
	3 (2)	1·5319	11	—	—	1·5450	17·5	13·5
	4 (1)	1·5334	13	—	—	1·5431	14	13·5
	5 (2)	1·5345	14	—	—	1·5434	15	14·5
	5 (3)	1·5437	28	—	—	1·5503	28	28
Felsite, Glen Cloy, Arran.	1 (3)	1·5496	41	—	—	1·5594	45	43·5
	2 (1)	—	—	1·5531	41·5	1·5569	41	41
	4 (1)	1·5455	34	—	—	1·5525	32	33
	5 (3)	1·5468	36	—	—	1·5538	34	35
	6 (1)	1·5464	35	1·5501	35	—	—	35
Pitchstone, Tenerife, Canary Is.	1 (1)	—	—	1·5528	41	1·5572	41	41
	2 (1)	1·5501	42·5	—	—	1·5577	42	42·25
	3 (1)	—	—	1·5508	37	1·5551	37	37
	4 (1)	1·5478	38	—	—	1·5561	39	38·5
	7 (1)	1·5473	37	—	—	1·5564	40	38·5
Porphyritic pitchstone, Brodick, Arran.	1 (1)	1·5364	18	—	—	1·5478	23	20·5
	2 (1)	1·5366	18	—	—	1·5434	14	16
	4 (1)	1·5368	18·5	—	—	1·5452	19	18·75
	5 (1)	1·5405	24·5	—	—	1·5470	22	23·25
	6 (1)	1·5346	14	—	—	1·5440	15	14·5
	7 (1)	1·5375	20	—	—	1·5449	17·5	18·75

always appreciated; in this case the matching point has been that of green light (it should of course be constant for any one observer). The strong zoning of the Ronez plagioclase makes any close agreement between the two sets of values unlikely.

Fig. 7 shows some results plotted on the Köhler curves of twin-pair angle against composition. The values are for albite and Carlsbad twin pairs for crystals from four of the rocks (the Ronez plagioclase was not

TABLE I (*continued*).

Universal-stage measurements (% An)					Universal-stage values minus refractive-index values.			
Composition plane		Twin plane			Composition plane		Twin plane	
(010).	Pericline.	(010).	(001).	⊥(001) in (010).	Chudoba.	Chayes.	Chudoba.	Chayes.
54	—	—	—	—	+6·0	+7·0		
47	—	—	—	—	+3·0	+3·0		
55	—	—	—	—	+6·0	+6·0		
49	50	—	—	—	+1·0 +2·0	+1·0 +2·0		
50	—	—	—	—	+4·0	+4·5		
				mean	+4·5	+4·5		
48	—	—	—	—	−3·0	−3·0		
40	—	—	—	—	−5·0	−5·0		
24	—	—	—	—	+4·25	+4·75		
13	—	—	—	—	−1·0	+1·0		
17	—	—	—	—	+3·25	+4·0		
14	—	—	—	—	+0·5	+2·25		
20	—	—	—	—	+5·5	+7·5		
32	—	—	—	—	+4·0	+3·0		
				mean	+1·0	+2·0		
44	—	—	—	—	+0·5	+0·5		
44	—	—	—	—	+3·0	+2·75		
41	—	41	—	—	+8·0	+7·5	+8·0	+7·5
42	—	—	—	—	+7·0	+6·5		
42	—	—	—	—	+7·0	+7·0		
				mean	+5·0	+5·0		
43	—	—	40	—	+2·0	+1·5		
43	—	42	—	37	+0·75	+0·25	−0·25, −5·25	−0·75, −5·75
45	—	—	42	—	+8·0	+7·75	+5·0	+4·75
42	—	—	42	—	+3·5	+3·0	+3·5	+3·0
45	—	—	42	—	+6·5	+6·0	+3·5	+3·0
				mean	+4	+3·5	+1·5	+1·0
34	—	—	—	—	+13·5	+14·0		
—	29	—	—	—	+13·0	+13·25		
31	—	35	—	—	+12·25	+13·5	+16·25	+17·5
37	—	30	—	—	+13·25	+14·25	+5·75	+7·25
34	—	30	—	—	+19·5	+20·25	+15·5	+16·75
29	—	—	—	28	+10·25	+11·25	+9·25	+10·25
				mean	+13·5	+14·5	+12·0	+13·0

suitably twinned). The curves $\alpha\alpha'$ and $\gamma\gamma'$ refer to the angles between the indices for the two individuals of an albite twin; $\alpha_1\alpha_2$ and $\gamma_1\gamma_2$ to the corresponding angles for the two parts of a Carlsbad twin. For the Stonehead gabbro crystals the value used for the composition was the mean of all refractive-index determinations; for the other three rocks the twin angles and composition were measured in each case on the same crystal: for all results the values were adjusted for sodium-light. The

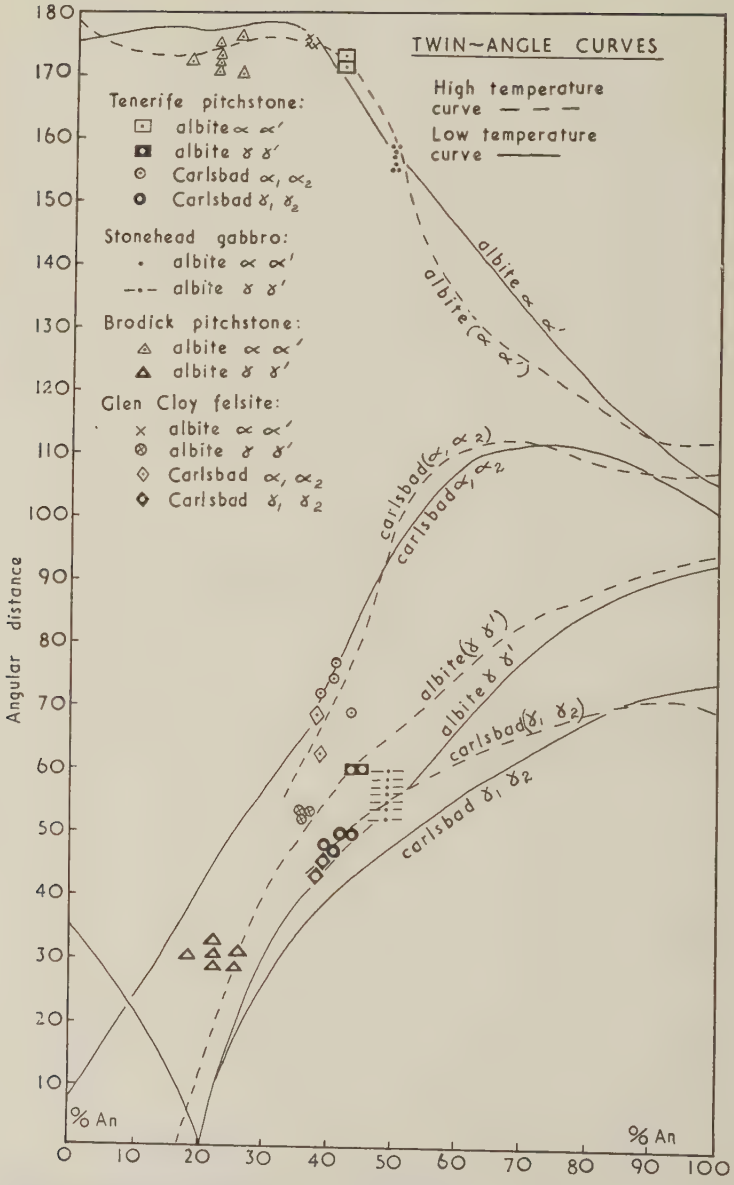

FIG. 7. Albite and Carlsbad twin-angles plotted on the Köhler high-temperature graphs.

results are highly interesting, but not always conclusive. The variation in optics between crystals from one rock is of the same order as the angular difference between the two curves, and it seems that it would generally be unwise to base conclusions about optics on one or two measurements only. The results may be summarized:

Stonehead gabbro.—Albite $\alpha\alpha'$ twin-angles fall at a point where the curves cross, those of $\gamma\gamma'$ extend from the low-temperature curve towards the high-temperature curve.

Tenerife pitchstone.—Albite $\alpha\alpha'$ and $\gamma\gamma'$ are high-temperature. Carlsbad $\alpha_1\alpha_2$ are apparently low-temperature (the two curves are close together at this point); $\gamma_1\gamma_2$ are high-temperature.

Glen Cloy felsite.—Albite twin-angles. $\alpha\alpha'$ are indeterminate, $\gamma\gamma'$ high-temperature. Carlsbad values are indeterminate. These felspars are so decomposed that it was difficult to obtain sufficiently accurate values; nevertheless there is again the general similarity between the Glen Cloy and Tenerife crystals that has been commented on before.

Brodick pitchstone.—The albite twin-angles are clearly those of high-temperature felspars. Here again there is more variation in optics between crystals than is desirable—in this case the difference in composition between adjoining albite twins undoubtedly contributes in part to this variation.

Conclusions.

High-temperature felspars have anomalous optics which may be recognized in at least three ways: twin- and composition-planes diverge from the standard Reinhard stereograms; composition determined from universal-stage stereograms differs from that given by refractive-index determinations; twin-angles fall on or near the high-temperature graphs of Köhler. It is probably unwise to rely on any one method exclusively. The Brodick pitchstone plagioclase is shown as high-temperature by all of these methods. The Stonehead gabbro, Ronez pegmatite, and Bushveld norite contain low-temperature crystals. The type of plagioclase from the Glen Cloy and Tenerife rocks is more difficult to ascertain. Crystals from both show a systematic displacement from the Reinhard curves and the Köhler twin-angles fit the high-temperature curves fairly adequately; on the other hand, there is no systematic difference in composition values obtained by different methods. It appears highly probable (from the X-ray work) that the distinction between high- and low-temperature plagioclase is brought about by an order-disorder transformation. The high-low albite relationship is believed to be an

Al Si order-disorder; the anorthite end of the series (An_{72-100}) has Al Si ordered throughout and the high-low changes are due to the disordering of some other group, presumably the cations. (This is in keeping with the larger optical differences between the high and low forms at the albite end of the series.) If this is the correct explanation of the high-low optics, then felspars in all states from the completely ordered low-temperature forms to the randomly arranged high-temperature forms will be found occurring naturally, the actual state of any given plagioclase being determined by its previous thermal history. The Glen Cloy and Tenerife crystals therefore show only partial disordering; the Brodick plagioclase is much more disordered—although even here the disorder is not necessarily as great as that found in an artificially prepared specimen. Alternatively there might be two types of disordering, only one of which shows the anomalous composition results.

It has previously been the custom to explain optical anomalies in the plagioclase series by the presence of other elements, notably potassium. There is no reason to doubt that the plagioclase lattice can tolerate a certain number of potassium atoms; it is not at all clear what effect this has on the optics, and it is hoped that it may prove possible to analyse the material from Brodick, Glen Cloy, and Tenerife to make sure that the optics have not been complicated by the presence of other elements. The variation in composition between adjoining albite twins is another factor which when it is better understood may be of value in interpreting conditions of petrogenesis. It is probably linked with the change from the albite-type to the intermediate-type structure. The particular composition at which this change in structure occurs may depend on the thermal history of the crystals.

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A large mineralized cavity in a tholeiite dike in Northumberland.

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Introduction.

TOWARDS the end of 1952 mining operations at West Sleekburn colliery, Bedlington, Northumberland, involved the driving of a drift through a 'whin' dike. In the process of doing so an unusual, large cavity was penetrated. When the cavity was first entered, by the manager and under-manager, it was found to be water-free but full of 'gas', which rendered them almost unconscious. Their exploration was therefore delayed until the gas was removed by pumping. Unfortunately no sample of the gas was collected, but it is thought to have been 'fire damp'. After examination the cavity repeatedly filled with gas, leading to a suspicion of a hidden extension to the cavity, under the roadway.

Mr. R. Beahey, in search of an explanation of the cavity, brought samples of the minerals to the Geology Department of King's College. The following is a record of the findings and results of the subsequent investigation.

Location and general description of the cavity.

The dike containing the cavity is one of the tholeiite dikes of the olivine-bearing Brunton type described by Holmes and Harwood.[1] It passes about a mile north of Bedlington and trends WNW.–ESE. (110–290°) and is normally about 30 feet thick, but in the vicinity of the cavity narrows to about 20 feet. The cavity is situated at lat. 55° 9′ 22″ N. and long. 1° 33′ 12″ W., and is found at a depth of about 100 fathoms, level with the Bensham coal seam.

The cavity is centrally placed in the dike. Its longest dimension, about 24 yards, is parallel to the dike walls. The other dimensions are variable. The maximum height is 12 feet and maximum width is 10

[1] A. Holmes and H. F. Harwood, The tholeiite dikes of the north of England. Min. Mag., 1929, vol. 22, pp. 1–52.

feet (figs. 1 and 2). The true length of the cavity is unknown, as the westerly portion disappears in a narrow sinuous passage, and the eastern end of the cavity was removed in driving the drift. It is also probable that there may be an extension downwards to the east which was covered when the cavity was broken into.

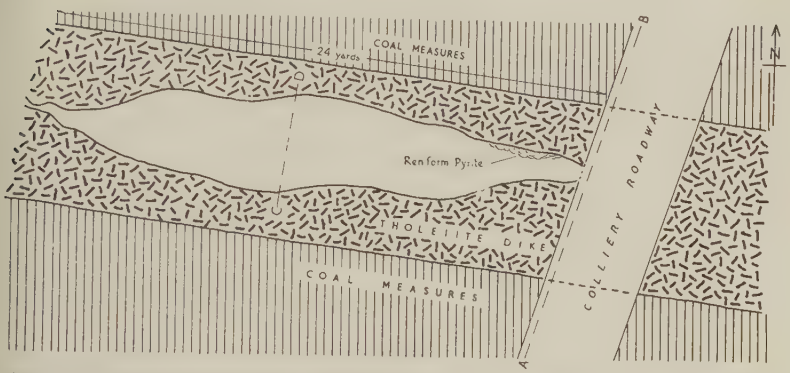

FIG. 1. Plan of cavity, showing relation of sections A-B and C-D in Figs. 2 and 3.

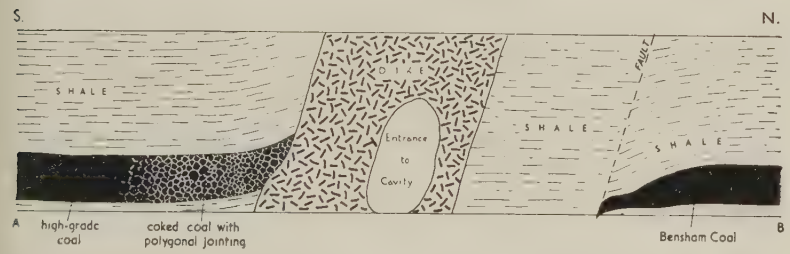

FIG. 2. Section A-B through cavity, as seen in roadway through the dike.

The coal on the northern margin of the dike is cut out by faulting, but on the southern margin it is hardly disturbed by the dike. It is, however, 'coked' for a distance of 10 feet and then passes abruptly into a high-grade coal in the manner described by Marshall.[1]

The minerals developed in the cavity are: pyrite, marcasite, ankeritic calcite, and a magnesium-rich ankerite. Generally their distribution is in three horizontal zones, as indicated in fig. 3.

[1] C. E. Marshall, The alteration of coal seams by the intrusion of some of the igneous dykes in the Northumberland and Durham coalfield. Trans. Inst. Mining Engineers, 1936, vol. 91, pp. 233-260.

Zone I.—The upper zone consists of a botryoidal development of pyrite and marcasite resting on a thin layer of carbonate. The sulphides tend towards a stalactitic development, especially at the top. The radial structure of the growth is obvious in a hand-specimen, and most of the surface shows an iridescence with blue and green tints. Platy, radial developments, characteristic of marcasite, are seen in certain parts of this zone. In one or two instances the marcasite growth has been sheathed with calcite and subsequently the marcasite has been removed, leaving the calcite in a form resembling platy baryte. In other places there is no development of the botryoidal material; instead a thin crust of pyrite rests on the carbonate layer. Sometimes the crust of pyrite is fractured and can be seen 'peeling', curling like dried orange skin, and simulating somewhat the leafy structures of zone II. About half-way down zone I is a shiny horizontal band 1–2 inches broad, lacking any trace of iridescence usually characteristic of the normal development.

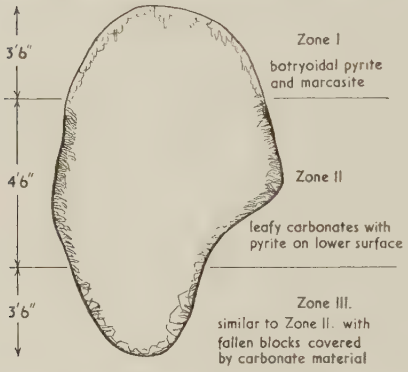

FIG. 3. Vertical section C-D (fig. 1) through cavity.

Zone II.—The middle zone has a well-defined boundary with zone I, but merges rather gradually downwards into zone III. This zone consists of a leafy development of the carbonate minerals standing out more or less horizontally from the walls. On the lower surface of the projections is a development of crystalline pyrite. Much of the material presents a brecciated appearance. Some of the material is very brittle, and breaks at the slightest touch.

Zone III.—The lower zone consists of similar material to zone II, together with fallen blocks of the dike, all coated with carbonate material. An unusual development occurs at the east end of the cavity on the northern wall. This consists of a massive growth of reniform pyrite covering an area of $10 \times 4\frac{1}{2}$ feet and merging to the west into the 'leafy' type of material. The south wall at this point has only a thin development of carbonate with very little sulphide material. The roof here bears small stalactites of carbonate. Carbonate stalactites are developed mainly in the eastern third of the cavity, the largest being

about 2 feet in length. Down the walls of the cavity are several 'streams' of carbonate.

At the west end, the cavity has no visible termination as it passes into a tapering sinuous channel only a few inches in diameter. In the last accessible portion of the cavity, which is actually in zone II, are some remarkable stalactites of carbonate coated with botryoidal pyrite. Near the cavity, the dike is considerably altered to white trap impregnated with pyrite and veined with calcite and pyrite.

Determination of the minerals.

The iridescent surface of the sulphide material suggested the presence of copper or nickel, but this was not substantiated by qualitative analysis. X-ray powder photographs of the reniform material (taken from a central layer) indicated pure pyrite, while the botryoidal material proved to be a mixture of pyrite and marcasite.

Fig. 4. Polished section of botryoidal sulphides illustrating radial structure in the marcasite.

The colour difference between marcasite and pyrite on freshly fractured surfaces was not regarded as a useful test,[1] since all the material had a fibrous, radial structure and material available for comparison was coarsely crystalline. The relation of the pyrite to marcasite was determined by the examination of polished surfaces under polarized light.

[1] F. A. Bannister, The distinction of pyrite and marcasite in nodular growths. Min. Mag., 1932, vol. 23, pp. 179–187.

In the botryoidal material the growth of the sulphides took place on a carbonate layer, commencing with pyrite, followed by oscillatory zoning of marcasite and pyrite, and terminating with a thin layer of marcasite. The actual structure of the marcasite as determined under crossed nicols is portrayed in fig. 4. The pyrite has a similar structure but due to its isotropic nature is only seen on poorly polished surfaces.

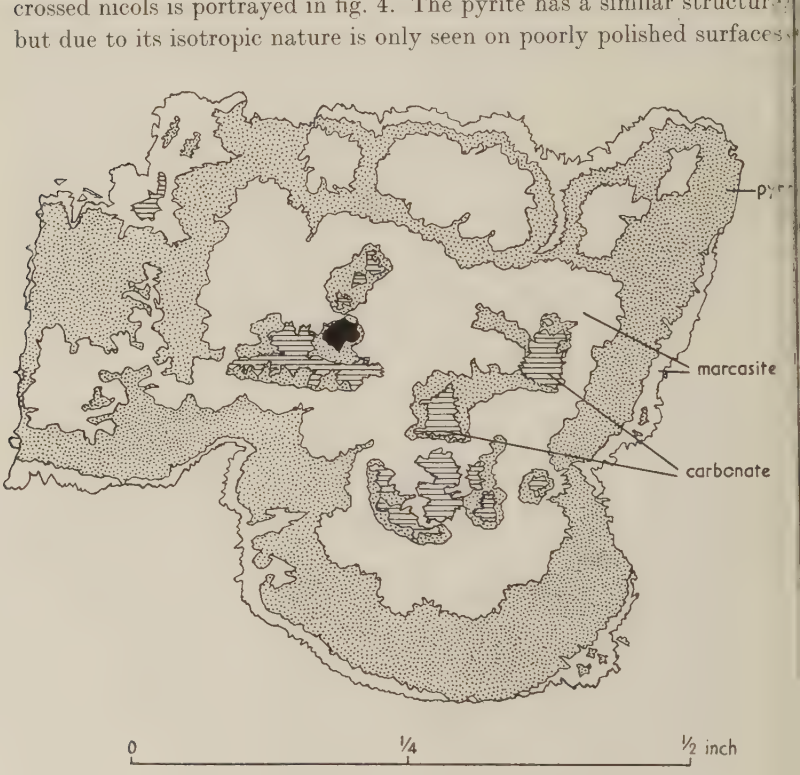

Fig. 5. Polished section of botryoidal sulphides.

The actual thickness of each layer is variable as represented in figs. 4 and 5. Polished sections of the reniform material showed that, although composed largely of pyrite, there are one or two thin layers of marcasite near the outside.

The 'leafy' material of zone II is composite in nature as is shown in the drawing of a thin section (fig. 6). Polished sections of the lower surface indicated that the sulphide is present mainly in the form of pyrite although some marcasite occurs. Above the pyrite layer is a fine-grained grey carbonate (A), then a thin discontinuous layer of

pyrite, and finally a coarser-grained, pearly carbonate layer (B) which forms the upper surface. The last forms a downward projecting lip on the edge of the leafy material and is crystallized as nail-head spar in parallel growths. When treated with hydrogen peroxide and concentrated potassium hydroxide the grey carbonate was stained, whilst the pearly carbonate remained almost unchanged.

Fig. 6. Thin section of leafy development.

On analysis, the grey carbonate (A) (table I) was shown to be an ankerite close to dolomite in composition. Its refractive index ω 1·682 is in agreement with that shown on a graph plotting ordinary ray refractive index against composition for ankerites by Smythe and Dunham.[1] The pearly carbonate (B) has ω 1·665 identical with that of the stalactitic material. On analysis the stalactitic material was shown to be an ankeritic calcite.

Table I. Chemical analyses of carbonates (calculated to 100 %).

Grey carbonate (A) from 'leafy' development (analyst, B. A. O. R.).		Ankeritic calcite, stalactitic material (analyst, J. A. Smythe).	
$CaCO_3$	62·46	$CaCO_3$	97·19
$MgCO_3$	32·27	$MgCO_3$	0·93
$FeCO_3$	5·27	$FeCO_3$	1·50
$MnCO_3$	n.d.	$MnCO_3$	0·38

Origin of the cavity.

In seeking the origin of the cavity the main characteristics of other similar cavities in dikes in Northumberland are important, so they are listed below. No record of cavities in dikes appears to have been made in the past by the mining industry, so it is highly probable that there

[1] J. A. Smythe and K. C. Dunham, Ankerites and chalybites in the northern Pennine orefield and the north-east coalfield. Min. Mag., 1947, vol. 28, pp. 53–73.

are many more that have been discovered and forgotten and so do not appear in the list.

1. Isabella shaft, Cowpen, 2½ miles SE. of Bedlington.—Discovered in 1940 or 1941, at the level of the Plessey coal seam, within 100 yards of the shaft. Dimensions: 40 yards long × 10 feet high × 5 feet wide. Mineralization: calcite as 1-inch dog-tooth crystals.

2. Horton Grange colliery, 2½ miles SE. of Bedlington.—Discovered in 1940 or 1941, at the level of the 5/4 seam. 30–40 yards × 9 feet × 4 feet. Calcite as white ½-inch dog-tooth crystals.

3. West Cramlington colliery, 4 miles S. of Bedlington.—At the level of the Low Main coal. Length not measured but extending for many yards, height about 6 feet, width 4 inches. Dog-tooth calcite and possibly some pyrite.

4. Hartford colliery. 2 miles S. of Bedlington.—Discovered between 1920 and 1925. At the level of the Plessey coal seam. Calcite only.

5. Backworth colliery, 6 miles NE. of Newcastle-on-Tyne.—Discovered 1946, at the level of the Beaumont seam. 5 × 4 × 1 feet. No mineralization.

6. Prosperous colliery, 6 miles NE. of Newcastle-on-Tyne.—Discovered 1946. About the same size as no. 5. No mineralization.

In each case the longest dimension of the cavity is parallel to the trend of the dike and the height is greater than the width. All dimensions given are maximum values. The cavities listed here have not been examined by the author as they either occur in abandoned areas or have been removed by mining operations. These appear to be the only cavities of any size known in dikes, yet dikes have been tunnelled in many areas, as, for example, in work for the hydroelectric schemes in Scotland, without reports of any cavities.

The author suggests that the presence of coal is essential in the formation of these cavities and that they result from coal being caught up by the magma during intrusion and being subsequently gasified. It would be expected that the greatest dimension of such a cavity would be parallel to the walls of the dike. Faulting, as a mechanism in the formation of these cavities, can be discounted, as differing orientations of the cavities would surely be expected, and at Sleekburn there is no evidence to support this.

Age and order of mineralization.

The mineralization is thought to be unrelated to the actual formation of the cavity. The development of horizontal zones clearly indicates that water has been a controlling factor during deposition. It is thought that the junction of zones I and II represents the general high-water level during mineralization and that the minerals above this line

developed in a gaseous environment. The bright line in zone I probably represents a fairly recent water level (before mining operations reduced the water table).

The leafy development in zone II probably represents growth of ankerite, crystallizing from the walls in a manner similar to formation of ice forming on the edges of a pond. This material is delicate and would have some support from the still water. Some of this material has collapsed and become cemented where it has fallen. The latest development has been the growth of the ankeritic calcite on the uppermost surfaces only, of the leafy development. This growth must have taken place in a water-free atmosphere as it develops an overhanging 'lip' to the leafy material. Accompanying this was the development of the calcite stalactites.

The alternate development of pyrite and marcasite in the botryoidal material suggests that there has been a series of oscillations from an alkaline to a weakly acidic environment, although these minerals may form together as is shown by the work of Allen et al.[1] The occurrence of the reniform material is puzzling. Its location may be governed by proximity to an inlet of solutions. It too, however, shows a change of environment near the end of its formation to more acid conditions.

Since all the minerals found in the cavity are very commonly developed in the Coal Measures, their occurrence in the cavity is not unexpected and suggests derivation from the surrounding strata.

Acknowledgements.—The author would like to express grateful appreciation to Mr. R. Beahey who originally notified him of the existence of the cavity; to the manager and under-manager of the West Sleekburn colliery for their help and willingness to allow visits to the cavity; and to numerous other people in the mining industry for information about the other cavities; to Dr. J. Shirley who accompanied the author on visits to the cavity and, together with other members of the departments of geology in Durham University, discussed the problem with him; to Dr. E. C. Ellwood for taking the X-ray photographs; and to Dr. J. A. Smythe for the ankeritic calcite analysis and for encouragement throughout the investigation.

Whilst all opinions expressed are those of the author, thanks are due to the Coal Board for permission to publish this communication.

[1] E. J. Allen et al., Amer. Journ. Sci., 1912, ser. 4, vol. 23, p. 169; 1914, ser. 4, vol. 28, p. 393.

A rapid method for the preparation of thin rock-sections

By E. O. Rowland

Department of Geology, King's College, University of London.

[Communicated by Dr. A. K. Wells; read June 11, 1953.]

THE basic technique for preparing micro-thin rock-sections has altered little since this method of studying rocks was first accepted. Abrasive powders were, and still are, used either on glass or metal plates, the grinding being done entirely by hand. At the present time carborundum is almost universally used as the abrasive. The technique has been speeded up somewhat by the use of horizontal metal laps, and in more recent years the introduction of high-speed diamond-cutting and lapping apparatus has considerably reduced the time involved in making a thin rock-section. But even with this apparatus the process is still long and laborious, and, even more important, the operator must have considerable skill and experience in keeping the specimen whole and of uniform thickness throughout the entire operation.

The writer is responsible for supervising the preparation of all rock sections, both for teaching and research purposes, in the Department of Geology, King's College, London. The difficulty has always been to keep the research worker supplied with sufficient sections to enable him to continue with his work. Using the existing technique of sectioning, including the use of high-speed cutting apparatus and horizontal rotary laps, the time spent in preparing a section from average material varies from half to one hour, friable material taking longer. This position made it desirable to look for mechanical and speedier methods of doing the rough grinding. Many previous attempts have been made to construct apparatus for this purpose. As far as can be traced all these methods have involved attachments to, and apparatus for use with, horizontal rotary laps. It is known that engineers in their work use surface-grinding apparatus involving vertical rotary grinding wheels and their finished products have to be true to a thousandth part of an inch. It was with this knowledge in mind that the writer constructed a metal holder on which a 3×1 inch glass slide could be held flat and secure. Such a slide, with a prepared rock specimen cemented thereon (in the conventional manner), was inserted in the holder and this was

then clamped on the table of a surface-grinding machine and an attempt was made to grind the specimen, using a wheel of 90 grit carborundum,

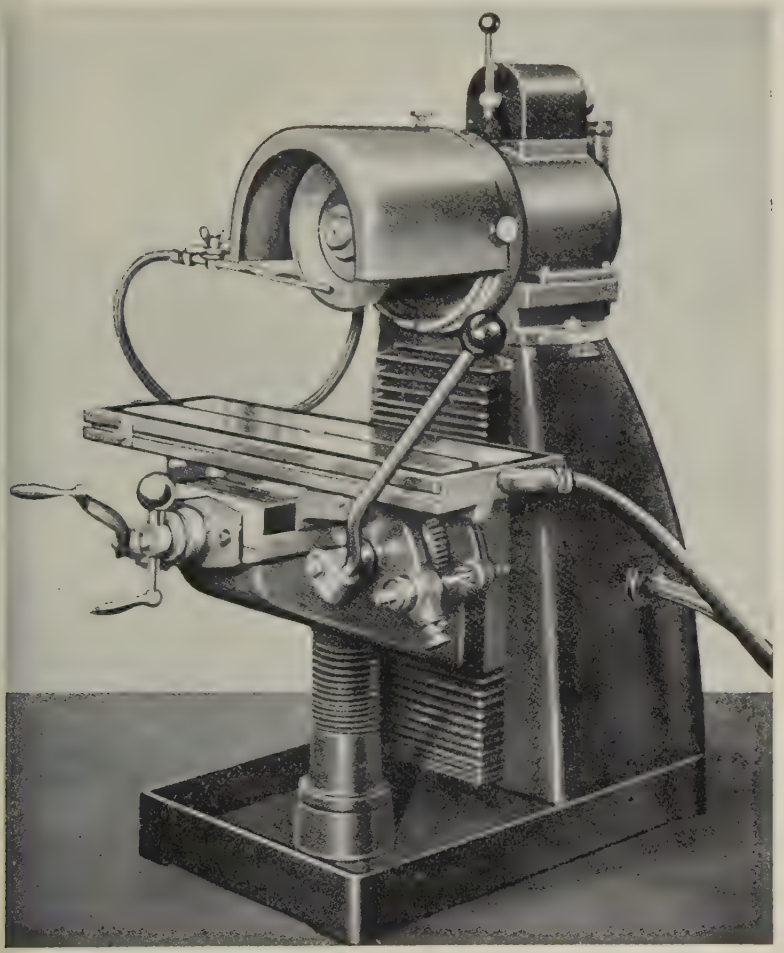

Fig. 1. The G.F.3 surface grinding machine. Overall height 31 inches; table space required 30×30 inches.

1 inch in width, rotating vertically at 2500 r.p.m. The result was disappointing. The wheel became hot at the point of contact and it was clear that the carborundum wheel was not suitable.

Using the same holder, a second attempt at surface grinding was

made. This time a modern grinding machine, the G.F.3, was used. This machine, illustrated in fig. 1, was supplied by the Impregnated Diamond Products, Ltd., and is already in use in a number of geological departments as rock-cutting apparatus. It consists essentially of a diamond-impregnated grinding wheel held rigidly above a table and rotating vertically. The table is capable of being raised and lowered to and away from the wheel, and also of being moved horizontally towards or away from the operator across the width of the wheel, both these movements being adjustable to a thousandth part of an inch. The grinding operation itself is hand-controlled by a lever that enables the operator to move the table backwards and forwards in the direction in which the wheel rotates. This particular machine is also fitted with a magnetic table. The holder is placed on the table and when the magnet is switched on it is pulled down absolutely level and held quite rigid. The grinding is then carried out, using a diamond-impregnated wheel, grade 140–160, $\frac{5}{16}$ inch in width, rotating at 3000 r.p.m., the point of contact being cooled by a jet of weak soluble oil.

The first results achieved with this machine proved most encouraging, so further tests were made to grind a rock specimen of basic material down to a predetermined thickness of 0·004 inch. This was carried out by first raising the table until the wheel was in contact with the surface of the glass slide, and then lowering it by 0·004 inch. The rock-section was then ground. Upon examination it was found that although about 40 % of the section had been ground completely away, the remainder (normally grey polarizing minerals) showed first-order colours. This was obviously due to the uneven thickness of the balsam beneath the section, as the glass slide itself was unaffected. By experiment it was found that the simplest method of avoiding this uneven distribution of balsam was by grinding a channel about $\frac{3}{4}$ inch wide and 0·002 inch deep across the glass slide. This channel is filled with balsam and the specimen is then pressed firmly down on to the glass, the specimen, of course, overlapping the channel (fig. 2). This method also proves advantageous in that, as there is virtually no balsam between the glass and the section, the thickness of the specimen after primary grinding can be quickly ascertained by measuring the complete thickness of the slide and specimen, and deducting the known thickness of the slide.

A new holder, fig. 3, was now made to enable three specimens to be ground at a time, the glass slides being held in position by a knurled-headed screw at each end, the tips of the screws being protected by fibre heads. These heads ensure the screw gripping the glass, so that in

practice it is only necessary to clamp down lightly. In order to facilitate examination under the microscope without removal from the holder, the latter was designed to fit on to the microscope stage, and holes were bored under the position of the centre of each specimen. The magnetic table ensures that the clamp is pulled down level again into the same position on replacement.

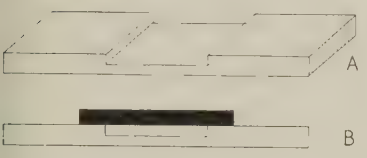

FIG. 2. A, 3×1 inch glass slide with channel ground to depth of 0·002 inch. B, The same in section showing the rock-slice overlapping the channel by approx. $\frac{1}{4}$ inch on each side. The channel has been exaggerated for illustrative purposes only.

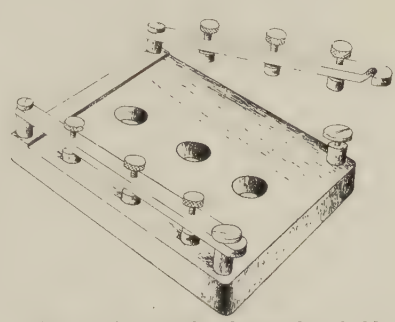

FIG. 3. The holder designed to hold three 3×1 inch slides during the grinding operation.

This method has been found entirely successful. It is possible to grind three sections at once, and grey polarizing minerals, such as quartz and felspar, show second-order colours (corresponding to a thickness of 60 microns) in a matter of two or three minutes, a uniform thickness, of course, being assured. The sections are then completed by hand, using the finest grade carborundum powder.

A variety of materials have been ground with equal success, including friable materials impregnated with shellac-balsam, dammar gum, and 'Lakeside 70'. It has been found that the wheel is much more efficient if it is kept well dressed back, this operation being carried out in a few moments during the grinding. The cleaning sticks used are cheap and obtainable from the makers of the machine.

It is essential that the 3×1 inch slides are of a uniform thickness all over. In practice it is a simple matter to check this thickness with a micrometer, and at the same time to grind out the channels. The slides are best dealt with in boxes of half a gross at a time, and the whole of the operation, including the checking of the thickness, can be completed in about half an hour.

During the grinding operation it sometimes happens that the ends of the glass slides become fractured. This presents no difficulty, however, as the section can be easily transferred by the following method. The writer normally transfers *all* finished sections. The surplus balsam is scraped away and the section is then carefully scrubbed (to remove abrasive grains), and lightly painted over with a solution of equal parts of amyl acetate and 'Durofix'. This dries in about thirty seconds and does not affect the refractive indices. It is then placed on an electrically heated hot plate (with a surface temperature of 100° F.) and a clean 3×1 inch slide placed beside it. Fresh balsam is applied to its surface and to the glass slide. When the balsam begins to run freely the section is gently moved over on to the glass with the mounting needle and the cover-slip is placed on in the usual manner. In the case of sections impregnated with 'Lakeside 70' it is necessary to turn the section over completely when transferring to the clean glass slide to release the air bubbles trapped on the under side, this operation being carried out with the aid of pointed forceps.

Acknowledgements.—I wish to thank Dr. A. K. Wells for the encouragement and for the helpful suggestions he has given. I should also like to thank my colleague T. W. Lewis for his co-operation, and B. Dawkins of the Impregnated Diamond Products, Ltd., for producing the holder and for his technical advice and guidance.

Note on the occurrence of beryl and löllingite at the New Consols mine, Stoke Climsland, Cornwall.

By P. G. Embrey, B.A., B.Sc., A.R.I.C.

Department of Geology and Mineralogy, Oxford University.

[Read June 11, 1953.]

SPECIMENS of the minerals beryl and löllingite were found by me among material collected in the summer of 1950 and the spring of 1951 for work on the distribution of trace elements in the New Consols mine, Stoke Climsland, Cornwall. Unfortunately, I was unable to collect further material, and in the case of the löllingite its presence on a specimen was recognized only after the mine had been abandoned and become flooded. This locality for the two minerals seems worthy of record in view of the small number of reported occurrences in Cornwall.

Beryl.

The beryl was found in specimens from a pegmatite vein, approximately 2 feet thick and dipping steeply southwards towards the main granite boss of Kit Hill, which was intersected 222 yards from the engine shaft by a south cross-cut at the 52-fathom level. Most of the pegmatite, which has an ill-defined junction with the surrounding killas, is a moderately fine-grained aggregate of quartz, albite, and sodic muscovite; the coarsely crystalline part of the pegmatite consists of irregular grains of milky quartz and platy aggregates of muscovite, and it is in these latter that the crystals of beryl are found.

The crystals of beryl are dirty greenish-white in colour, and most of them are well-defined hexagonal prisms up to 6 mm. long and 4 mm. in diameter; no terminal pyramid faces could be detected, only the basal cleavage being present. Identification rests on the optical and other physical properties, and spectrographic determination of beryllium, aluminium, and silicon. Thin sections prepared from individual crystals (no beryl was to be found in thin sections of the pegmatite) show that they are extensively altered along an irregular network of cracks to kaolinite, and contain numerous hair-like liquid inclusions. Interference figures show the crystals under examination to be biaxial negative, with a small optic axial angle.

Other minerals present in small amount on the specimens are tourmaline, pale-purple fluorite, arsenopyrite, and a thin coating of chalcopyrite and blende on a joint face.

In the summer of 1951 Sir Arthur Russell collected specimens from a pegmatite vein 8 inches thick which had recently been cut during the extension of a north cross-cut at the 64-fathom level, rather more than 300 yards from the engine shaft. These specimens show a close similarity to those from the thicker pegmatite vein one-third of a mile to the south; the main difference lies in the presence of a greater amount of pale-blue and purple fluorite. One specimen shows a little granular pyrite, and another what appears to be a single small plate of pyrrhotine.

A careful examination of the specimens has failed to reveal any other beryllium minerals from the New Consols mine.

St. Michael's Mount has been known as a locality for beryl for many years,[1] and is referred to by J. Garby[2] together with Mabe and Constantine parishes near Falmouth. Greg and Lettsom[3] repeat this list, with the addition of Wheal Castle, near St. Just. More recently, J. Robson[4] adds Long Downs, near Mabe, as a separate locality, but Sir Arthur Russell[5] regards the Mabe and Constantine occurrences as incorrect, probably due to confusion with apatite. The only other recorded localities in Cornwall have been given by P. K. Ghosh[6] ('very limited' in heavy residues from the Bodmin Moor granite), A. F. Hallimond[7] (Beam mine, St. Austell), and J. Phemister[8] (South Crofty mine, Camborne). A pale greenish prism of beryl in granite from Swit quarry, Craddock Moor, Bodmin Moor, was presented by P. K. Ghosh in 1927 to the British Museum mineral collection.

[1] A. R. Barclay, Beryl in Cornwall. Ann. Philosophy, 1825, ser. 2, vol. 10, p. 383.

[2] J. Garby, A catalogue of minerals found in Cornwall, with their localities. Trans. Roy. Geol. Soc. Cornwall, 1848, vol. 7, p. 98.

[3] R. P. Greg and W. G. Lettsom, Manual of the mineralogy of Great Britain and Ireland. London, 1858, p. 126.

[4] J. Robson, Cornish mineral index. Trans. Roy. Geol. Soc. Cornwall, 1949, vol. 17, pt. 8 (for 1948), p. 464. [M.A. **11**–273.]

[5] A. Russell, Topaz from Cornwall, with an account of its localities. Min. Mag., 1924, vol. 20, p. 225.

[6] P. K. Ghosh, Petrology of the Bodmin Moor granite (eastern part), Cornwall. Min. Mag., 1927, vol. 21, p. 308.

[7] A. F. Hallimond, Note on a specimen of white beryl from Beam mine, St. Austell, Cornwall. Min. Mag., 1939, vol. 25, pp. 351–352.

[8] J. Phemister, Note on an occurrence of bertrandite and beryl at the South Crofty mine, Cornwall. Min. Mag., 1940, vol. 25, pp. 575–578.

Löllingite.

Some time ago I was asked by Sir Arthur Russell to check whether some specimens he had collected from Castle-an-Dinas wolfram mine, St. Columb Major, in 1937 were in fact löllingite or arsenopyrite. Following on from this investigation, X-ray powder photographs were taken of my arsenopyrite specimens from New Consols mine, Stoke Climsland;

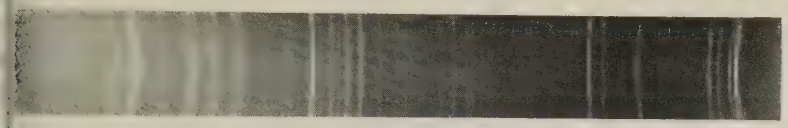

Fig. 1. X-ray powder photograph (cobalt radiation) of löllingite from Castle-an-Dinas mine, Cornwall. (High-angle end on the left.)

by a coincidence, the only one which had not been analysed spectrographically for trace elements was found to consist mainly of löllingite, with a little intergrown arsenopyrite. It may be mentioned in this connexion that the X-ray powder data obtained from the Castle-an-Dinas material (which showed no arsenopyrite lines in the pattern, fig. 1) correspond almost exactly with those given by M. A. Peacock,[1] while the American Society for Testing Materials data are in complete disagreement. Specific gravity determinations on the Castle-an-Dinas löllingite failed to give a value higher than 7·12, probably owing to the porous nature of the material; the highest value which the New Consols löllingite yielded was 7·08, but the separated material in these determinations always contained an appreciable amount of arsenopyrite.

The specimen of löllingite from New Consols, which was the only one found in the mine, came from a part of the main lode one foot from the hanging-wall, in a stope 70 feet above the 40-fathom level and 700 feet east of the engine shaft. The bulk of the specimen consists of finely granular löllingite with no well-formed crystals; on a partially polished surface coarse grains of arsenopyrite may readily be distinguished by the naked eye (taking a polish more easily than the surrounding löllingite), while under the microscope intergrowths on a smaller scale are seen to be present. Small amounts of chalcopyrite and pyrite are also present on the specimen. The arsenic minerals, from their observed relationship with the neighbouring gangue, appear to have replaced the brown

[1] M. A. Peacock, On the identification of minerals by X-rays. Trans. Roy. Soc. Canada, 1941, ser. 3, sect. 4, vol. 35, p. 111. [M.A. 8–280.]

quartz-tourmaline 'capel'; sharp grain boundaries between the löllingite and quartz may, however, be seen in one or two places. No general conclusions may be drawn from this isolated occurrence as to the role of löllingite in the mineralization of the New Consols lode.

This discovery of löllingite at New Consols confirms the observation by J. H. Collins[1] that it 'probably [occurs in] many other Cornish mines' having frequently been mistaken for arsenopyrite; he records the occurrence of löllingite ('leucopyrite') at East Pool and Dolcoath mines, and C. Le Neve Foster[2] gave Pedn-an-Drea mine as another locality. The occurrence at Castle-an-Dinas wolfram mine has previously been noted by J. Robson.[3]

In 1935 Sir Arthur Russell collected a specimen of löllingite, which has recently been identified by G. F. Claringbull, from the Tregargus china-stone quarry, St. Stephen-in-Brannel; in this case the mineral forms a granular coating on a joint face on a block of partially altered granite, and is intergrown with quartz, felspar, and a little purple fluorite. I have been asked to put this occurrence on record. In the mineral collection of the British Museum there are specimens of löllingite from Wheal Sparnon, Redruth.

[1] J. H. Collins, A handbook to the mineralogy of Cornwall and Devon. Truro and London, 1871, part II, p. 62.

[2] C. Le Neve Foster, On some new mineral localities in Cornwall and Devon. Min. Mag. 1877, vol. 1, p. 74.

[3] J. Robson, Trans. Roy. Geol. Soc. Cornwall, 1947, vol. 17, pt. 6 (for 1946), p. 347; 1949, vol. 17, pt. 8 (for 1948), p. 456. [M.A. **11**–273.]

A granophyre from Coire Uaigneich, Isle of Skye, containing quartz paramorphs after tridymite.

(With Plate XIII.)

By L. R. Wager, M.A., Sc.D., F.R.S., D. S. Weedon, B.A., F.G.S., and E. A. Vincent, M.A., Ph.D., A.R.I.C., F.G.S.

Department of Geology and Mineralogy, University Museum, Oxford.

[Read March 26, 1953.]

THE narrow belt of granophyre lying to the west of Blaven in the Isle of Skye showed so admirably the effects of chilling that a series of specimens was collected by one of us (L.R.W.) and found to contain, in the chilled marginal rock, phenocrysts of tridymite, now inverted to quartz. In the Thulean Tertiary igneous province former tridymite is known from certain acid lavas, for example, the Tardree rhyolite (von Lasaulx, 1877) and certain Icelandic liparites (Hawkes, 1916), and from metamorphosed arkoses adjacent to basic igneous intrusions (Harker, 1908, 1932), but it has not previously been noted in the intrusive acid rocks. In addition to phenocrysts of tridymite inverted to quartz, there is present in the groundmass of the unchilled granophyre a second generation of inverted tridymite crystals, surrounded by a final stage of quartz and felspar which has crystallized with normal microgranitic textures. Some of the textural features resemble those of the normal Skye granophyres, while others resemble certain metamorphosed arkoses.

Field occurrences.

The material studied was all collected in the neighbourhood of the col between Blaven and the basalt hills of An Stac and An da Bheinn (fig. 1). Here the granophyre is about 100 yards wide and is intruded into basalts, the parallel, steep-sided margins of the intrusion dipping at 80° to the ESE. (fig. 1, inset). The contacts with the basalt on both sides are sharp, and marked chilling of the granophyre has occurred to give a dark, flinty rock. The strongly chilled rock extends for about a foot into the granophyre and then gradually, over a distance of about six feet, gives place to a normal-looking, rather fine-grained granophyre.

Small platy phenocrysts may be seen in the chilled rock, which have some degree of parallelism with the boundary wall of country-rock. In

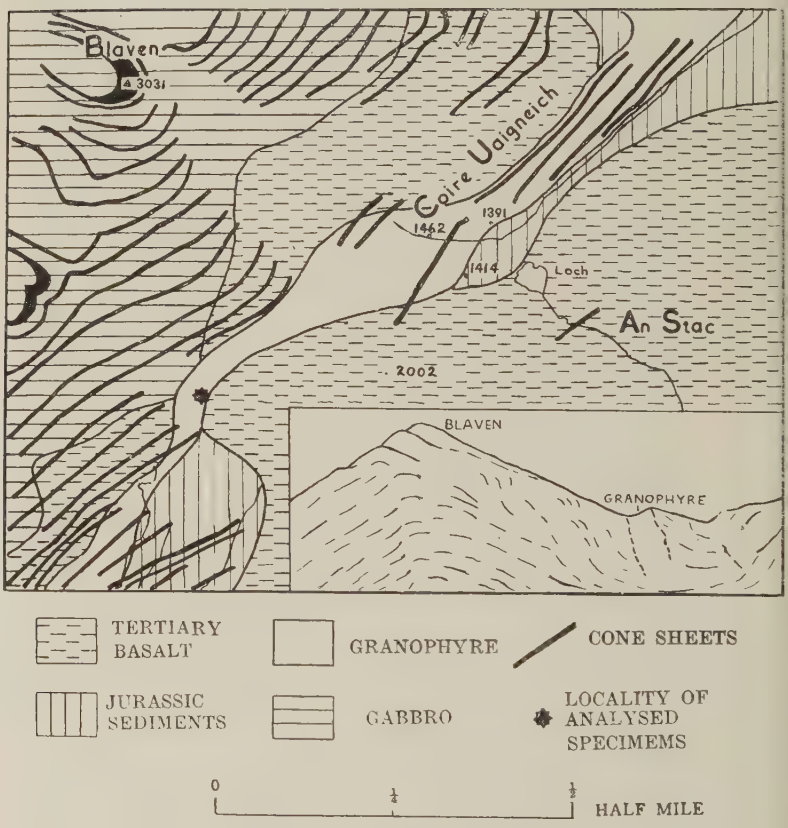

FIG. 1. Outline map of the Coire Uaigneich area, based on the maps of the Geological Survey. Inset: appearance of the area from the SW.

the central part of the granophyre the phenocrysts cannot be detected in the field and the rock appears uniform.

The granophyre examined forms part of a narrow intrusion mapped

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FIG. 2, B and B′. Main unchilled granophyre, showing development of criss-crossing tridymite crystals and the parallel relationship of some of them to the original tridymite phenocrysts. Areas of quartz and felspar with microgranitic texture are also shown. In B′, note that the same quartz unit may partly replace both the phenocrystic and the attached groundmass tridymite. B, ordinary light; B′, crossed Nicols.

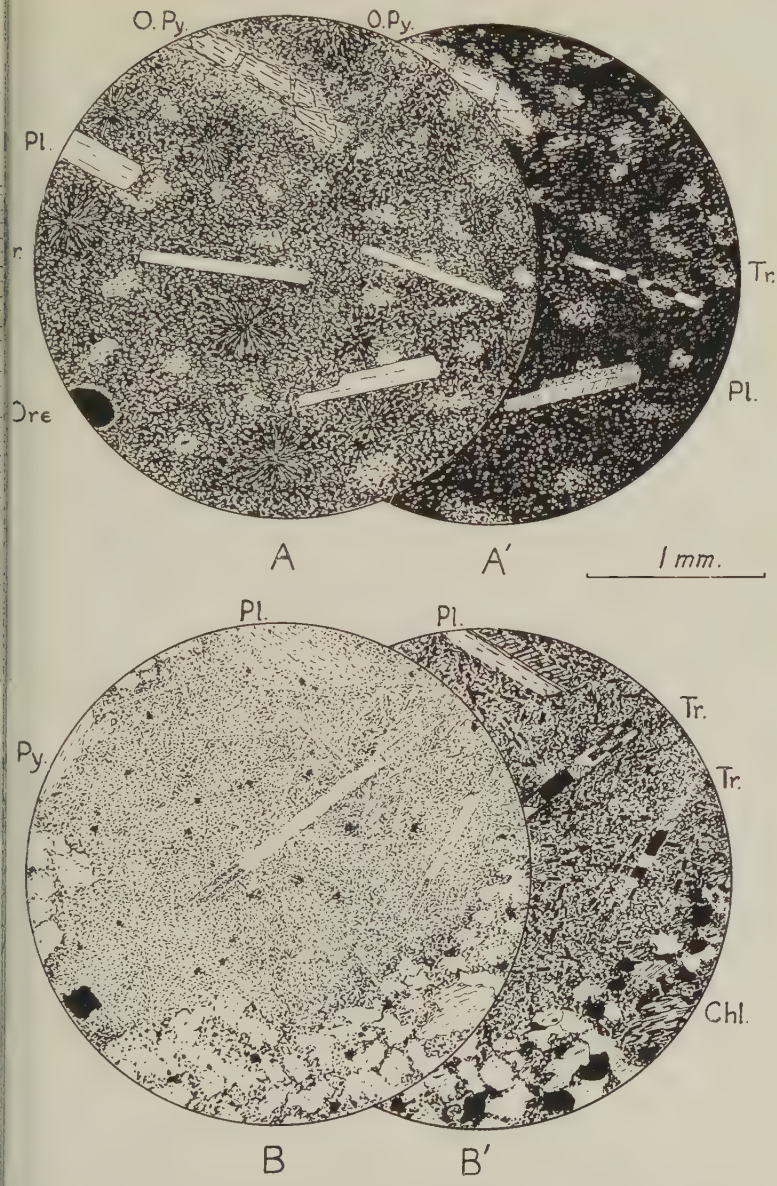

FIG. 2, A and A′. Chilled margin, showing phenocrysts of plagioclase (Pl), orthopyroxene (OPy), tridymite (Tr), and ore in a cryptocrystalline groundmass. Note the several quartz units now composing the tridymite crystal. A, ordinary light; A′, crossed Nicols. [FIG. 2, B and B′. *For description see opposite.*]

by Harker as extending for 3 miles to the NNE. and varying from 100 yards to a third of a mile in width (fig. 1). A rapid traverse along it suggests that the whole of this granophyre is essentially one mass; also it seems probable from petrographic similarities that the small area of granophyre to the west of Camasunary belongs to the same intrusion (unpublished thesis by J. M. Carr). To the east of Blaven the intrusion dips away from the Cuillins, the presumed centre from which it came, and it therefore appears to have a ring-dike form. Harker's map shows the granophyre to be cut by cone sheets and we have confirmed this. Richey (1932, p. 75) pointed out that this distinguishes it from the main granites and granophyres of Skye and suggests an earlier age.

The chilled margin.

The flinty chilled margin of the granophyre, in thin section, shows phenocrysts of felspar, tridymite now inverted to quartz, orthopyroxene, and iron-ore, set in a dense, dark-coloured cryptocrystalline groundmass (text-fig. 2, A and pl. XIII, fig. A). The orientation of the tabular felspars and inverted tridymites roughly parallel with the wall-rock is taken as indicating viscous flow.

The felspar phenocrysts (2·7 % by volume) are fairly thick, tabular crystals usually showing combined Carlsbad-albite twinning, the albite twin units often being very thin lamellae. Most crystals also show slight, continuous normal zoning. In all sections of the chilled granophyre studied, the felspar phenocrysts are fresh and gave the following data: $2V_{\gamma} - 75°$; maximum extinction angle in the zone $\perp$ (010) is $\alpha' : (010)$ 30°. This represents andesine-labradorite (approximately $An_{50} \pm 3$ %), and for felspars of this general composition, the optical data we have obtained does not make it possible, at present, to distinguish between high- and low-temperature types.

The former tridymite phenocrysts usually appear in thin section as narrow rectangular areas averaging 0·5 mm. in length, but broader sections and even rather irregular hexagonal sections are occasionally seen, depending presumably on their orientation relative to the section. The phenocrysts must be plate-like in form with a thickness approximately one-tenth or less of the diameter. In all cases the tridymite has inverted to quartz, the original tridymite crystal now being represented by many individual quartz units (text-fig. 2, A′). In the average elongate section, the long sides are definite, whereas the ends are not so clearly

bounded, implying that the (001) faces of the original tridymite crystals were better developed than the faces at right angles to them.

Ray (1947), reporting on quartz paramorphs after tridymite from a quartz-latite-porphyry in Colorado, states that the *c*-axis of the quartz had a preferred orientation of 61° ± 5° to the *c*-axis of the original tridymite plate. Ray investigated cases where each tridymite crystal had inverted to one quartz unit, but some degree of similar orientation is found in the Skye rocks where many individual quartz units replace a single tridymite crystal. By orientating sections of the chilled marginal phase of the Skye granophyre on the universal stage to give sections parallel with the *c*-axis of the original tridymite plate, it has been possible to plot stereographically the *c*-axes of the quartz units as angular distances from the *c*-axis of the original tridymite. The following results were obtained:

Angular distance from *c*-axis of original tridymite crystal ...	0–10°	10–30°	30–50°	50–70°	70–90°
Number of *c*-axes of quartz units	0	3	10	22	11

This would seem to indicate that, as Ray found in the case of single crystal paramorphs of quartz after tridymite, there is a limited degree of preferred orientation at approximately 60° to the original *c*-axis of the tridymite phenocrysts in the Skye example.

The orthopyroxene, modal amount 0·6 %, occurs as idiomorphic crystals with $2V_\alpha$ 51°, n_γ 1·716. These optics indicate a composition of 58 % $MgSiO_3$ according to Hess (1952) and, adopting Poldervaart's nomenclature (1947), it is named hypersthene. There is a varying amount of alteration to a bastite-like material.

Iron-ore, modal amount 0·7 %, occurs as rather rounded crystals up to 0·3 mm. across which are frequently rimmed by biotite.

The groundmass is cryptocrystalline with several minute crystals occurring in the thickness of the slice (pl. XIII, fig. A). Presumably it is composed largely of quartz and felspar, made dark with small magnetite crystals. Occasionally there are slightly coarser areas in which chlorite may be identified.

Traced inwards from the margin the rock quickly becomes less flinty and lighter in colour (pl. XIII, fig. B). Within a foot of the margin, the plagioclase begins to alter along cracks and the hypersthene becomes completely altered to bastite. For some feet, however, the groundmass remains essentially cryptocrystalline, a texture contrasting markedly with that found in the unchilled granophyre, next to be described.

The main granophyre.

The main granophyre, as we shall term the unchilled material, shows where we have studied it in the region of the col, areas having two generations of tridymite crystals, side by side with other areas having the typical microgranitic structure of the normal Tertiary acid rocks of Skye. The phenocrysts so well seen in the chilled rock are still present in the main granophyre, although greatly altered. The tridymite phenocrysts have the same form and are similarly inverted to quartz: the scattered andesine phenocrysts are present but replaced by a cloudy acid felspar, the refractive index of which is less than Canada balsam: the hypersthene crystals are present but completely converted to bastite. The rest of the rock has crystallized with two different textures (text-fig. 2, B and pl. XIII, fig. C): two-thirds consists of patches in which criss-crossing thin lamellae of inverted tridymite crystals are dominant: the remaining third, which is, in general, interstitial to the criss-crossing tridymite patches, consists of quartz and felspar with a rough micrographic texture.

The criss-cross crystals of the groundmass could not have been identified with certainty as former tridymite if tridymite phenocrysts had not originally been present, as it is their relation to the phenocrysts which proves their origin. Thus the inverted tridymite phenocrysts often have thin outgrowths of the same dimensions and general form as the criss-cross pseudomorphs of the groundmass (text-fig. 2, B). These extensions, which may be confidently interpreted as former tridymite crystals, are now quartz, sometimes in optical continuity with quartz units replacing the tridymite phenocrysts. This detail of texture makes it clear that the acicular-looking crystals of the groundmass were originally a second generation of small tridymite plates which crystallized from part of the magma surrounding the phenocrysts and which later inverted to quartz.

All the felspars of the groundmass have a lower general refractive index than quartz, and must be a potash-soda-felspar, presumably a cryptoperthite. There may be some small difference in composition of the felspars of the groundmass, as that part which is enclosed in the criss-cross tridymite areas is less cloudy with inclusions than that in the microgranite areas, but no precise optical data have been obtained.

Metamorphosed Torridonian arkoses having related textures.

Harker has described and figured the results of the metamorphism of Torridonian arkoses in the Isle of Rhum (1908, pp. 61–67). In a later

description of this rock (1932, p. 68) he ascribed the elongated quartz crystals to inversion from tridymite. Other examples have been described by M. K. Wells (1951, p. 720) and we have ourselves examined several cases from the metamorphosed Torridonian arkose adjacent to the basic complex of Rhum. A fairly typical example from within 10 feet of the contact with the eucrite in Allt Mor-n-h-Uamha, east of Allival in Rhum, is figured here (pl. XIII, fig. D). In hand-specimens the rock is beginning to have the appearance of a miarolitic granophyre; under the microscope areas of fritted quartz representing some of the original detrital grains can be seen, together with patches having a criss-cross arrangement of quartz after tridymite closely resembling that of the Coire Uaigneich granophyre. There are also areas showing a micropegmatitic intergrowth of quartz and acid felspar comparable with those found in the final stages of crystallization of the Coire Uaigneich granophyre. These similarities in texture suggest that the metamorphism, at its maximum, must have resulted in liquefaction of a considerable part of the arkose, otherwise the structures would be unlikely to resemble so closely those found in the granophyre produced by crystallization from a liquid.

Chemical composition.

Chemical analyses of the chilled marginal facies, and of the main granophyre from the central part of the intrusion, are given in table I, analyses 1 and 2. Their close similarity is at once apparent, and there can be little doubt that the two rocks originated from a common magma, an inference also drawn from the similarity of the phenocrysts.

The presence of andesine-labradorite and hypersthene in the chilled marginal rock might perhaps have been taken as some indication that the granitic magma involved would prove to be richer in basic oxides than usual, and in fact it is richer in MgO and CaO, although poorer in Na_2O and K_2O than the other Skye granites analysed. These differences, surprisingly, are not accompanied by low silica, the percentage of which, on the contrary, is high. If the normative plagioclase composition of the granophyre (Ab_{75}-Ab_{78}) is referred to the thermal equilibrium diagram for the plagioclases, it is seen that the appropriate plagioclase to crystallize first from a liquid of this composition, ignoring the effects of other constituents, would be An_{65}—so that the presence of phenocrysts at least as basic as the andesine-labradorite of the chilled marginal rock is to be anticipated. It is interesting that the early crystallizing pyroxene should be a hypersthene. Clinopyroxenes of diopside-heden-

TABLE I. Chemical analyses of the granophyre of Coire Uaigneich, Blaven, Skye, with some comparisons.

	1.	2.	A.	B.	C.	D.	E.
SiO_2	74·47	74·22	75·80	74·88	76·41	71·68	70·34
Al_2O_3	11·32	11·07	12·45	12·73	11·71	12·55	13·18
Fe_2O_3	2·06	1·75	1·47	0·53	1·68	2·29	2·65
FeO	2·22	2·43	0·44	1·33	0·77	2·40	2·24
MgO	0·78	0·74	0·08	0·25	0·17	0·24	0·40
CaO	1·69	1·56	1·00	1·12	0·42	0·92	1·24
Na_2O	2·79	2·95	2·30	3·33	3·62	4·28	3·61
K_2O	3·44	3·42	4·17	4·99	4·92	4·37	4·90
H_2O^+	0·47	0·90	1·30	0·79	0·50	0·64	0·76
H_2O^-	0·04	0·04	0·80	0·16	0·12	0·25	0·46
TiO_2	0·67	0·77	trace	0·18	0·14	0·38	0·46
P_2O_5	0·06	0·09	trace	0·05	0·04	0·03	0·10
MnO	0·06	0·06	0·017	0·02	0·002	0·05	0·19
others	—	—	—	—	—	—	Cl 0·02
Total	100·07	100·00	99·83	100·36	100·50	100·08	100·55
Norm (C.I.P.W.):							
qu	39·87	39·11	44·21	32·94	35·34	27·10	27·01
or	20·30	20·20	24·65	29·47	29·03	25·80	28·91
ab	23·57	24·96	19·45	28·30	30·60	36·15	30·49
an	7·98	6·79	4·95	5·00	1·11	2·06	5·22
cor	0·06	—	2·33	—	—	—	—
di	—	0·32	—	0·71	0·54	2·18	0·24
hy	3·30	3·42	0·20	1·82	0·17	1·44	2·40
mt	2·99	2·56	1·41	0·70	2·09	3·32	3·85
ht	—	—	0·50	—	0·24	—	—
ilm	1·28	1·47	—	0·46	0·26	0·71	0·87
ap	0·13	0·20	—	—	0·10	0·07	0·24

Mode (volume %) of H291 (analysis 1). Phenocrysts: felspar 2·7, pyroxene 0·6, ore 0·7, tridymite 1·7, total phenocrysts 5·7 %. Groundmass: 94·3 %.

1. Chilled marginal granophyre (H291), Coire Uaigneich, Blaven, Skye. Analyst: E. A. Vincent (new analysis).

2. Granophyre near centre of intrusion (H289), Coire Uaigneich, Skye. Analyst: E. A. Vincent (new analysis).

A. Rhyolite, New quarry, Tardree Mountain, Co. Antrim. Analyst: W. H. Herdsman. (Holmes, 1936.)

B. Biotite-hornblende-granite, Kilchrist, Skye. (Beinn an Dubhaich mass). Analyst: Geochemical Laboratories. (Tilley, 1949.)

C. Porphyritic felsite (H868), Harker's Gully, Marsco, Skye. Analyst: E. A. Vincent (new analysis).

D. Pyroxene-granophyre, G^2 (H932), SE. face of Beinn Dearg Mhor, Skye. Analyst: E. A. Vincent (new analysis).

E. Hornblende-granophyre, Druim Eadar da Choire, Skye. Analyst: W. Pollard. (Skye Memoir, 1904.)

ergite type are usual in the Skye pyroxene-granites and granophyres, nd orthopyroxene does not appear to have been noted elsewhere.

In table I are also listed analyses of certain other Skye granites, and f the Tardree rhyolite, Co. Antrim, for purposes of comparison. Harker, n the Skye memoir (1904, p. 153), observed that the British Tertiary ranites fell into a more acid and a less acid group. Examples of the ormer are afforded by the granites of St. Kilda, the Mourne Mountains, nd northern Arran, and in Skye by the Beinn an Dubhaich mass. A ecent analysis of the last granite is given as analysis B in the table, while analysis C is of another silica-rich granitic rock from Skye—the porphyritic felsite of Harker's gully on Marsco. While these two nalyses are roughly comparable with those of the Coire Uaigneich granophyre in silica percentage, they are poorer in iron and magnesium nd significantly richer in the alkali metals. Analyses D and E represent nore normal types of Skye granophyre, and belong to the less acid group of Harker. In these rocks, iron and magnesium contents are comparable with those of the Coire Uaigneich granophyre, while the higher potassium and sodium contents, on the other hand, resemble those of the Beinn an Dubhaich granite and the porphyritic felsite of Marsco. Other, as yet unpublished, analyses of Skye granites show these same general characteristics. Thus, as far as is shown by data at present available, the formerly tridymite-bearing granophyre of Coire Uaigneich has a bulk chemical composition significantly different from that of other Skye granites and granophyres.

It has some similarities with the rhyolite of Tardree Mountain, Co. Antrim, also a tridymite-bearing rock, although here the tridymite occurs in fissures and cavities and not as phenocrysts or in the groundmass (von Lasaulx, 1877). The Tardree occurrence is thus different from the lavas carrying tridymite described from the West Indies by MacGregor (1938) and from the San Juan region in Colorado by Larsen (1936).

Some of the differences in chemical composition of the Skye granophyres are significantly displayed when the normative (weight %) contents of quartz, orthoclase, and albite are plotted on a triangular diagram (fig. 3). The thermal relationships between these three components in dry melt are known from Schairer's (1950) work on the system SiO_2–$KAlSiO_4$-$NaAlSiO_4$. In the phase diagram for this system there occurs a low-temperature 'trough', within the stability field of the alkali-felspars. Barth (1951) has plotted normative proportions of quartz, orthoclase, and albite for various granitic and rhyolitic rocks

on this diagram, and has shown that the majority fall in or near t[illegible] low-temperature trough. The Skye granite analyses also fall in or ne[illegible] this trough, except for the Coire Uaigneich granophyre, which, with t[illegible] Tardree rhyolite, falls outside the trough towards the SiO_2 corner of t[illegible]

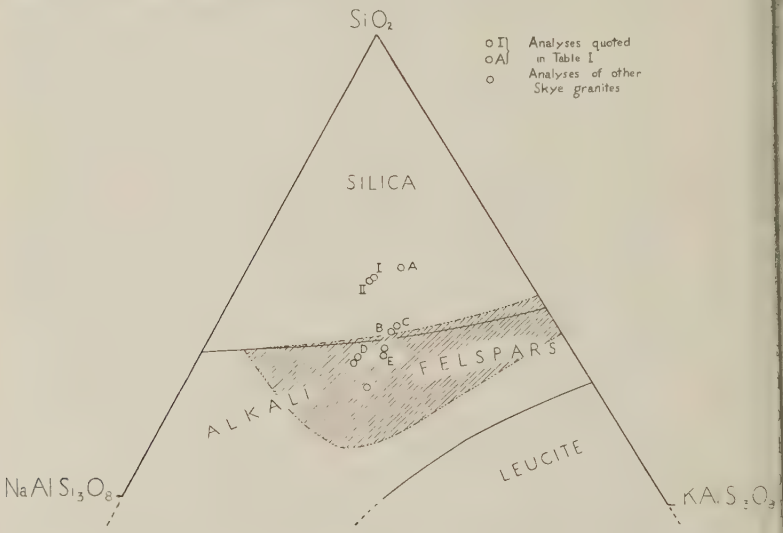

FIG. 3. Portion of the phase diagram SiO_2–$KAlSiO_4$-$NaAlSiO_4$ (after Schairer, 1950). The area below the 1050° C. isotherm ('low-temperature trough') is shaded.

triangle. Although having a slightly higher silica content than the Coire Uaigneich granophyre the analyses of the Beinn an Dubhaich granite and porphyritic felsite of Marsco (table I, B and C) fall nearer the trough, because their alkali content is relatively high and much SiO_2 is used in building the normative felspars, leaving less as excess quartz.

From the work of Fenner (1913) and others it is clear that tridymite forms as a metastable phase below its minimum temperature of existence as a stable mineral. Thus no absolute temperatures may be inferred from the presence of tridymite when considering the cooling history of this Skye granophyre. Whether tridymite crystallized or not is likely to be a complex function of temperature, composition, and the amount of fluxes present. In the SiO_2–$KAlSi_3O_8$-$NaAlSi_3O_8$ portion of Schairer's dry-melt phase diagram the appropriate form of silica in the region of the plotted points for the Coire Uaigneich granophyre is tridymite and the temperature of the beginning of crystallization lies between 1200°

nd 1300° C. It is not suggested that there is any close correspondence etween these temperatures and the actual temperature of crystallization of the Coire Uaigneich granitic magma, but it is likely that magma f this composition would crystallize at higher temperatures than normal ranite and it is of interest that in the particular case here considered ridymite crystallized as the early phenocrystic material.

Conclusions.

From the textures described it is clear that tridymite, andesine-labradorite, hypersthene, and iron-ore crystals were just beginning to precipitate from the Coire Uaigneich granite magma when it was implaced. Close to the cold country-rock, the magma with its enclosed crystals was apparently chilled rapidly, probably through several hundred degrees, giving, as a temporary stage, a glass. Thereafter, cooling of the marginal material would be slower, the glass being devitrified at some stage, say at a temperature of 200-300° C., to give the cryptocrystalline groundmass now found (pl. XIII, fig. A). A little farther from the margin (pl. XIII, fig. B), chilling caused by the cold country-rock would be less marked, but still the temperature of the liquid seems to have been carried rapidly down below that required for the formation of tridymite before appreciable crystallization took place. Still farther in from the margin a stage is reached where chilling was less rapid and minute crystals of tridymite had time to form in continuation of the phenocrysts, although the majority of the liquid solidified below the tridymite range. The main part of the granophyre, away from the effects of rapid chilling, would cool more uniformly, and here the textures are typically as shown in pl. XIII, fig. C. While about two-thirds of the liquid crystallized, tridymite was precipitated especially around the original tridymite phenocrysts, giving the criss-crossing tridymite areas. In the later stages, while the remaining third of the liquid crystallized, quartz, not tridymite, was precipitated, together with felspar and chlorite, giving the areas of microgranitic texture. These may reasonably be considered to have resulted from crystallization of a wetter residual liquid at relatively low temperatures. At some stage, apparently prior to the final quartz-felspar crystallization, the tridymite inverted to quartz. It was probably at this stage also that the plagioclase phenocrysts and perhaps also early groundmass felspars were made over to more acid felspars, and hypersthene was replaced by bastite.

The higher-temperature criss-cross tridymite texture is found in th later differentiates of the Skaergaard intrusion, east Greenland. Acic lar quartz was described from high ferrogabbros and figured from th andesine-andesite (Wager and Deer, 1939, p. 116 and pl. 19, fig. 1). was stated at the time that the significance of this texture was no understood. Re-examination now makes it clear that the acicu quartz must have inverted from tridymite, and no doubt other examp will be found in the mesostases of quartz-bearing intermediate rocks.

Evidence for the ultimate origin of the Coire Uaigneich granite mag is not provided by the observations here recorded—only the existe of a granite liquid carrying 5 % of crystals when intruded into it present position can be inferred, the chilled contacts clearly preclud any hypothesis of the generation of the magma in situ. Fusion Torridonian sandstone adjacent to the basic rocks of Rhum seems t have produced a liquid capable of crystallizing with a mineralogi composition and texture similar in significant ways to this grani magma. It should also be remarked that shadowy relics of an arko have been found in the main part of the Coire Uaigneich granophyr although not as yet in the marginal chilled material. Rocks such as th Coire Uaigneich granophyre, having a composition falling outside th usual eutectic compositions of granites, are not likely to be late residu from a crystal fractionation process, and perhaps in this granophyre w are studying a magma formed by refusion of an original, quartz-ric material which has not suffered appreciable subsequent fractiona crystallization. A study of trace elements in the Skye granophyres Torridonian arkose, and acid Lewisian gneiss, which is in progress, ma perhaps provide useful evidence on the problem of the ultimate origi of some of the acid magmas of the British Tertiary igneous province.

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Explanation of Plate XIII.

Photomicrographs of former tridymite-bearing granophyre from Coire Uaigneich, Skye, and of arkose with tridymite from Rhum.

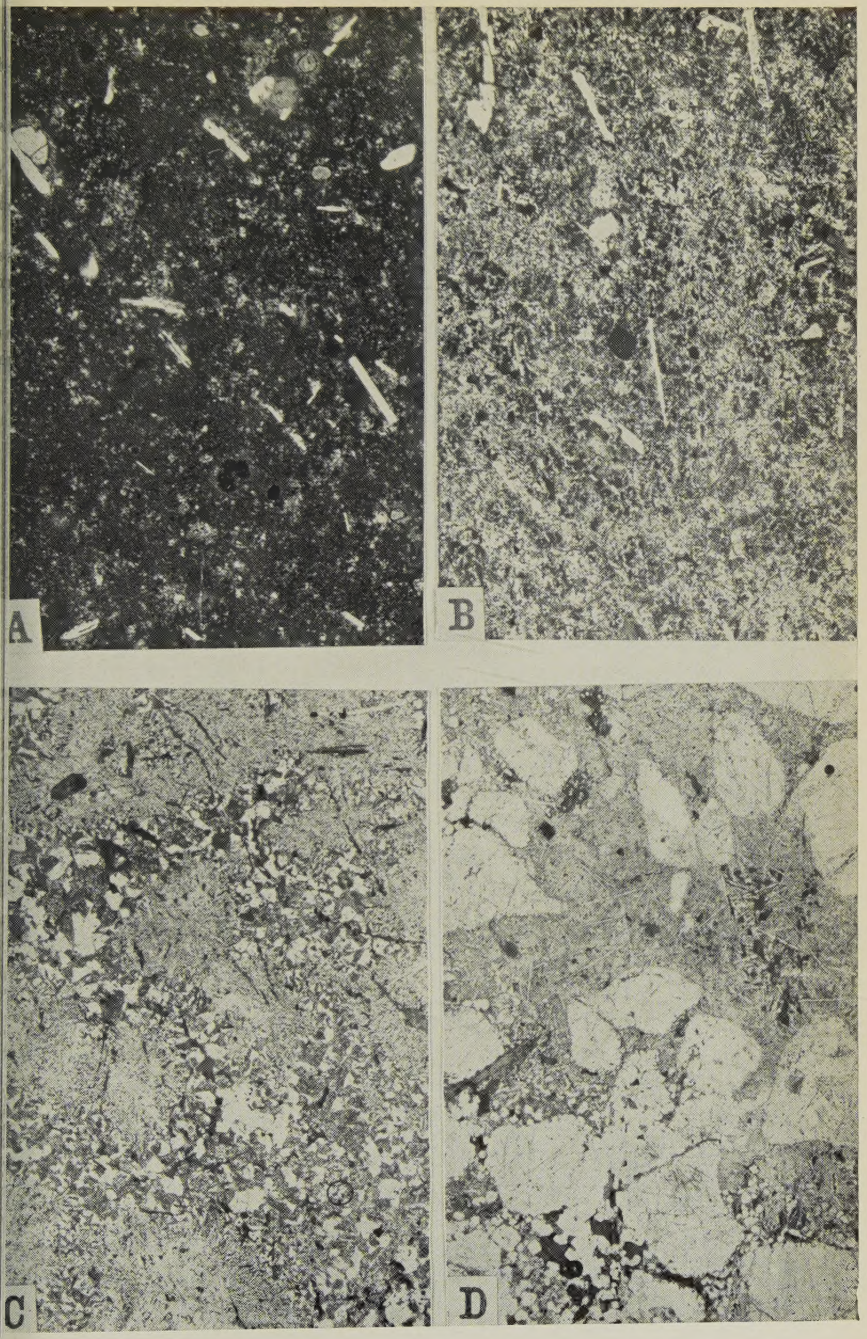
Fig. A. Chilled marginal granophyre with phenocrysts of replaced tridymite, plagioclase, hypersthene, and ore in a cryptocrystalline groundmass. (H 4180.)

Fig. B. Granophyre, about 2 feet from the margin; the groundmass is slightly more crystalline, but the phenocrysts, except the tridymite, are still unaltered. (H 290.)

Fig. C. Main unchilled granophyre, showing areas composed partly of criss-crossing, inverted, tridymite crystals, surrounded by areas of normal granophyric quartz and felspar. (H 289.)

Fig. D. Metamorphosed Torridonian arkose, Allt Mor-n-h-Uamha, Rhum, showing corroded, original quartz grains surrounded by areas with tridymite crystals and others of quartz and felspar with microgranitic texture. (H 3144.)

All photographs in ordinary light. Magnification $\times 17$.



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Tridymite in Granophyre and Arkose